Status and future strategy for advanced high power microwave sources for accelerators

Frank Gerigk, CERN, Switzerland

IPAC 2018, 30 April, Vancouver, Canada

Material from:

Olivier Brunner, Eric Montesinos, Carlo Rossi, Igor Syratchev, Helga Timko from CERN, and Mats Lindroos, Anders Sunesson from ESS

Disclaimer:

A personal “CERN-centric” view,
which does not cover everything.

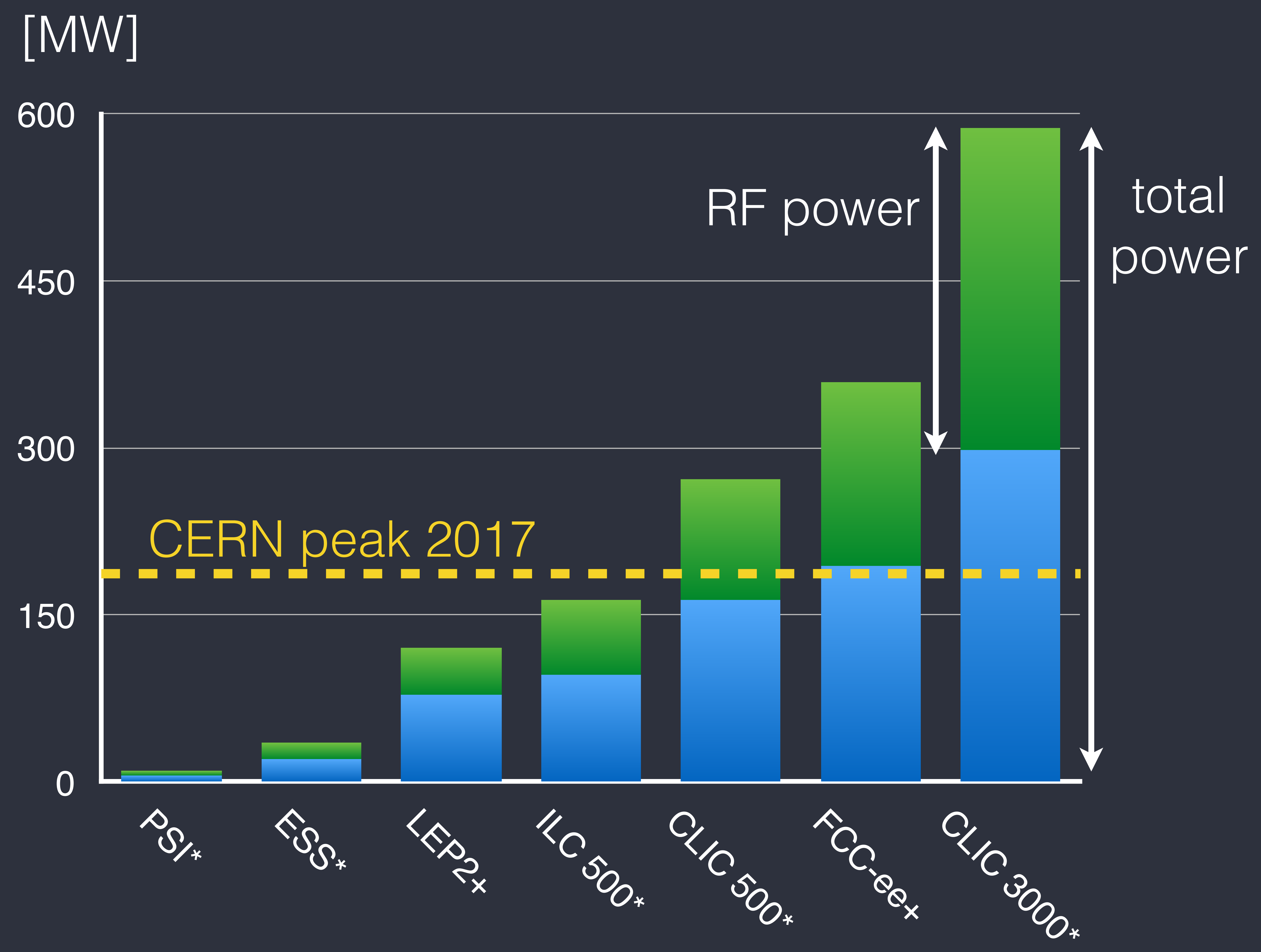
Content

The need for high-efficiency RF sources

RF power for selected accelerators

Project	P_{tot} [MW]	P_{RF} [MW]	P_{beam} [MW]
PSI*	10	4	1.3
LEP2+	120	42	19
FCC-ee+	359	165	100
ESS*	35	15	5
CLIC 500*	272	109	9.8
ILC 500*	164	68	9.4
CLIC 3000*	582	289	28

* facility power with experiments
\+ without injector



RF power cost

- **LHC with injectors:** needs ~1.1 TWh/year, 6% for RF.
- **CLIC 3000:** needs **2.74 TWh/year,** roughly the same as the whole canton of Geneva (~500 k people), **50% for RF: 187 M€***.

➡RF system efficiency is crucial for electron colliders and high-power hadron machines.

*Using today's EU average price for non-household electrical power (0.1€/kWh)

Today's RF sources

and ongoing developments

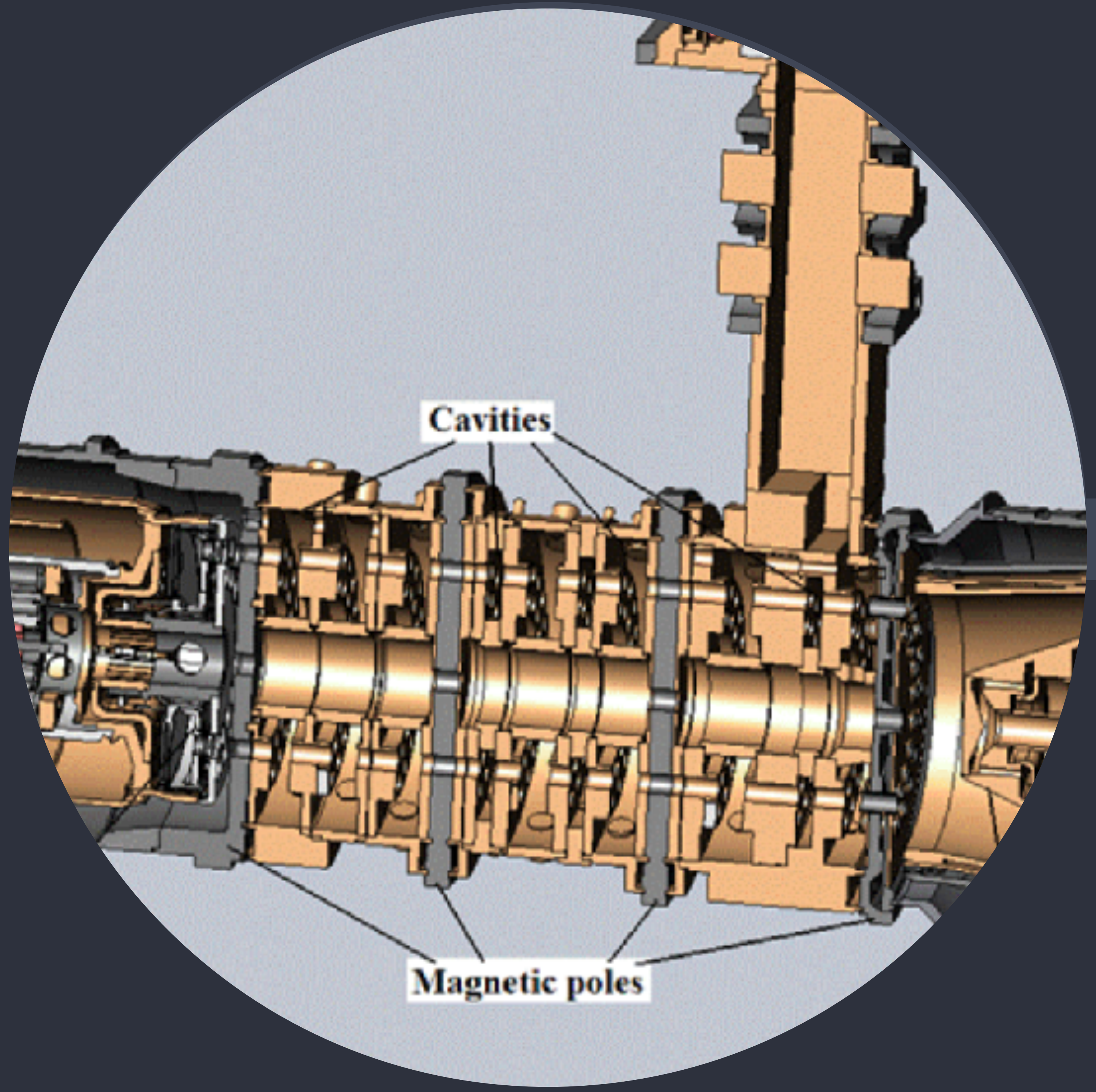
- Modulators
- Klystrons
- Gridded tubes: tetrodes, diacrodes®, IOTs
- Magnetrons
- Solid state

Modulators

“Modulate” the AC grid voltage to the voltage & time structure needed by the RF power source

Modulator technologies

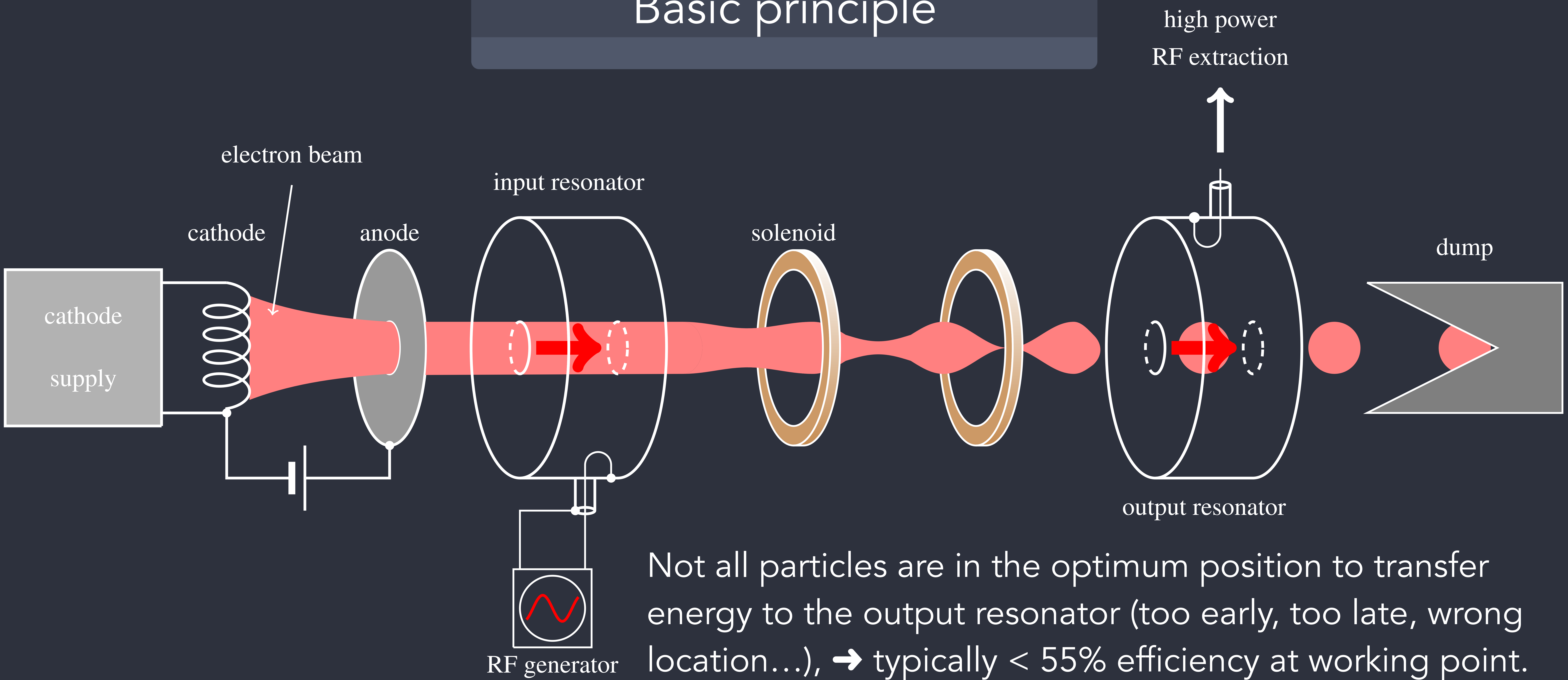
- **CW or gridded tubes** (no "modulation" or pulse "taken" by the tube): basically HV power supplies,
- **Pulsed operation of non-gridded tubes** (pulse is formed by the modulator):
  - **Pulse transformer** based: ~85 - 90% efficiency, multi-MW level, long rise times: ~300 us (for a reasonably sized transformer)
  - **HF transformer** based: resonant polyphase (SNS) or stacked Multi-Level (ESS): 90 - 92%, multi-MW level, short rise time (110 us).
  - **Transformerless**: direct switch design or MARX modulators, with potential for even higher efficiency.
- In general **85% - 92%** efficiency seems to apply to **all types of modulators** (solid state power supplies to klystron modulators), power levels and duty cycles.
- **Rise times** can increase power consumption. Lower voltage favours shorter rise time.



Klystrons

- Principle published in 1935 (O. Heil, Germany)
- Development of first klystron in 1937 (Russel & Varian, Stanford, USA)
- Higher efficiency & higher power

Basic principle

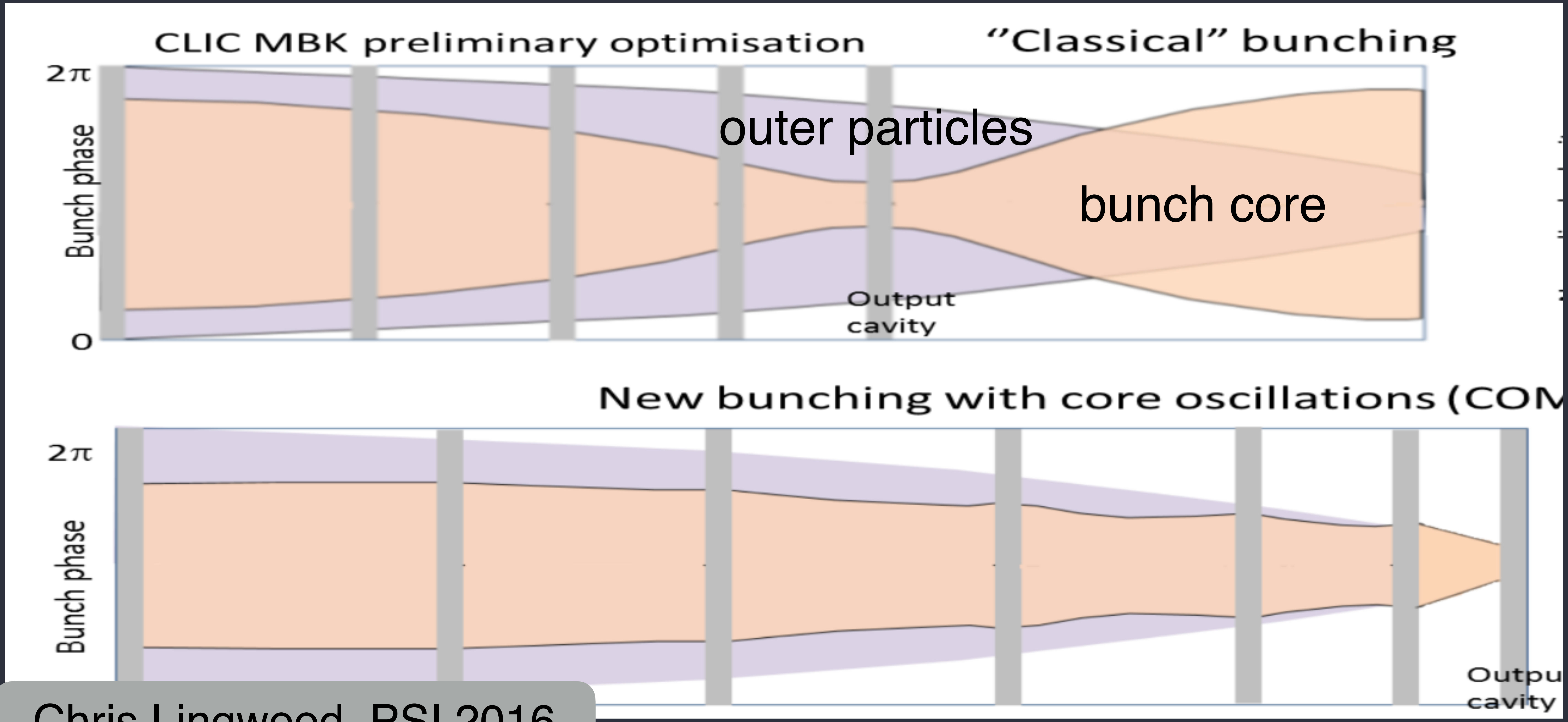


Not all particles are in the optimum position to transfer energy to the output resonator (too early, too late, wrong location…), ➜ typically < 55% efficiency at working point.

Modern beam dynamics tools allow optimisation beyond classical klystron limitations:
➜ 3 new principles

Core Oscillation Method (COM)

Core oscillates periodically with lattice, while outer particles are focused monotonically towards the centre. COM synchronizes the 2 processes.



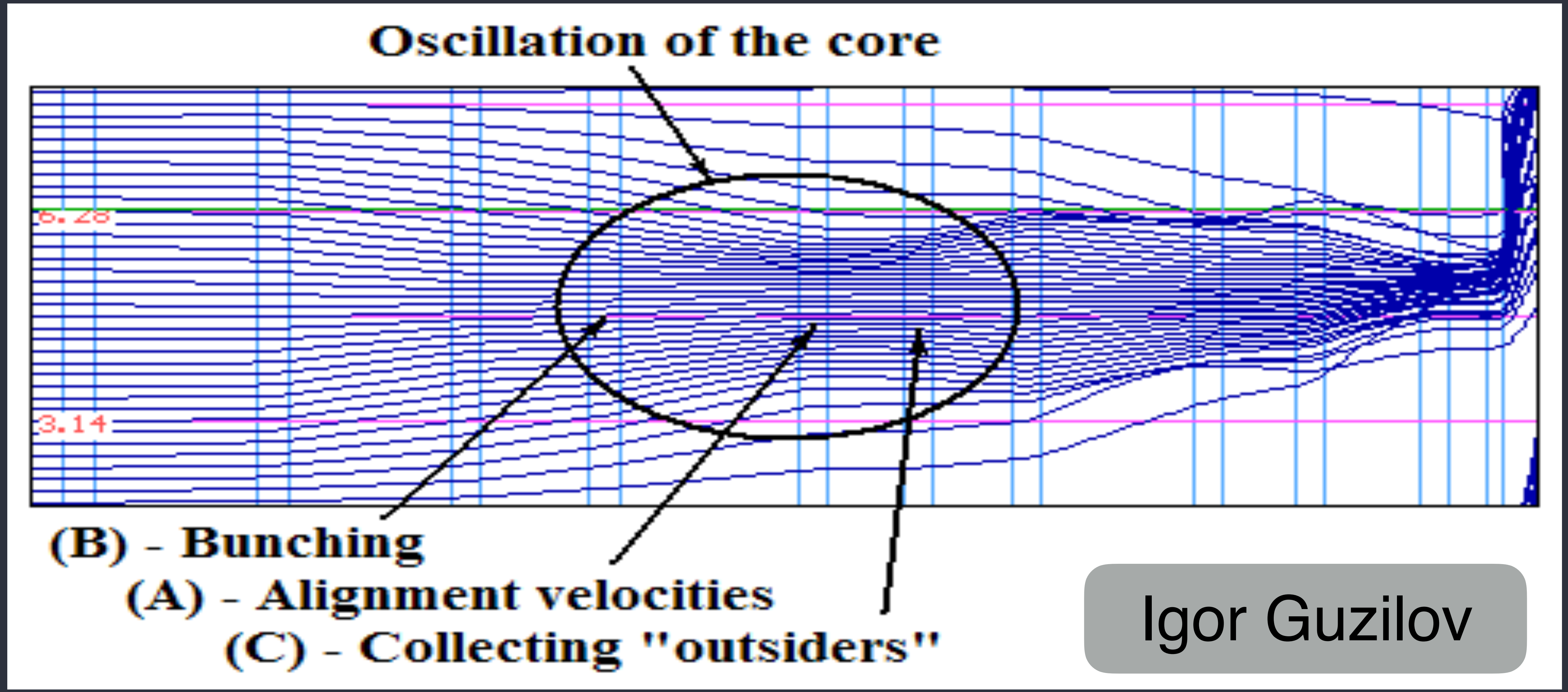
Chris Lingwood, PSI 2016

Advantage:
simulations predict efficiencies above 80%

Disadvantage:
very long tubes.

BAC method by I. Guzilov

Bunching, **A**lignment of velocities, **C**ollecting outsiders:
use the tuning of the intermediate cavities to create artificial oscillations



Igor Guzilov

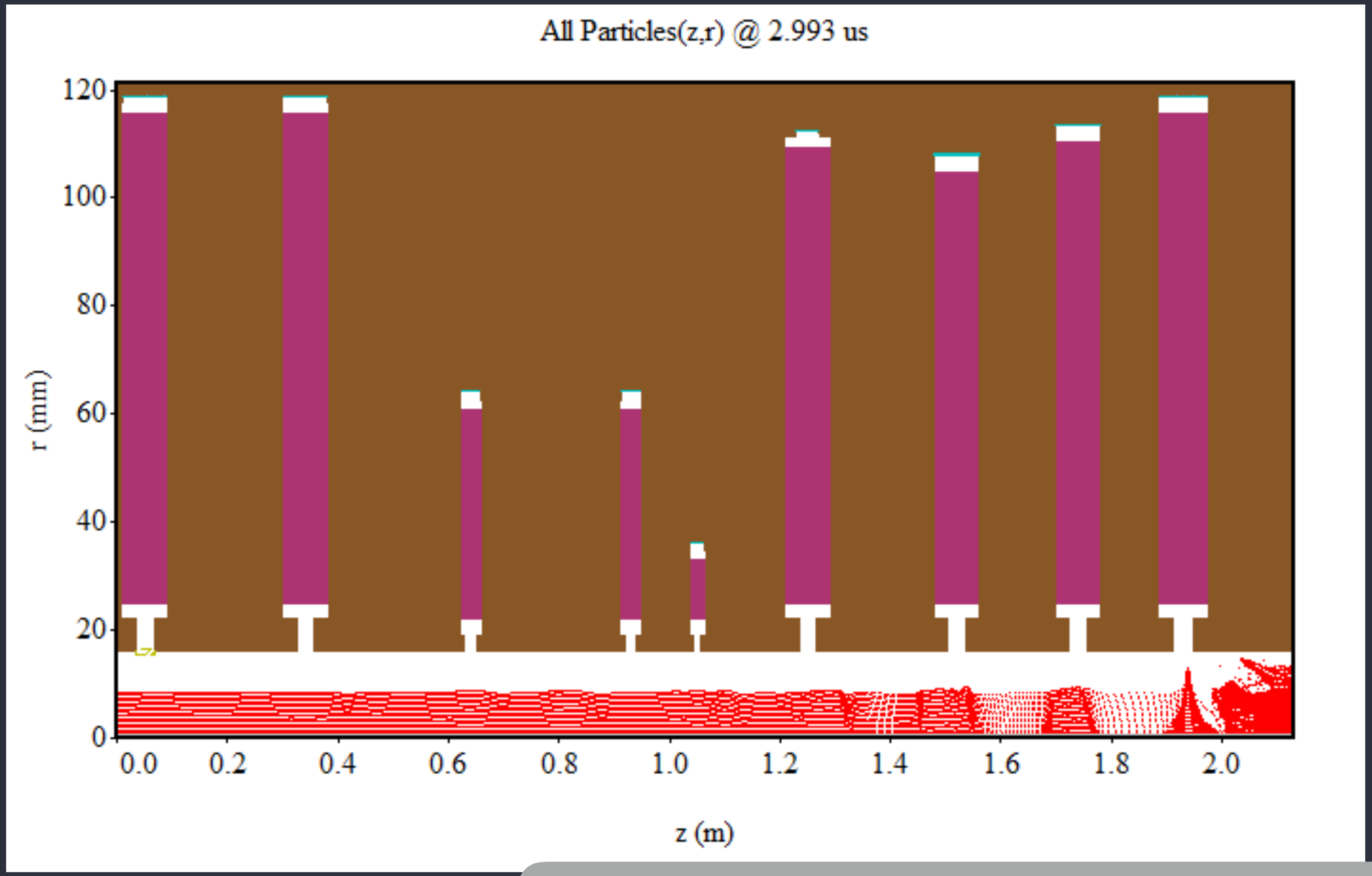
Advantage: Length reduction by over 50% when compared to COM, plus significant voltage reduction

Disadvantage: high number of cavities

III Core Stabilization Method

CERN development

CSM uses harmonic cavities (n=2,3) to do what space charge does for COM but in a much shorter distance.



Chiara Marelli, ESS seminar, 2016

Advantage: Efficiencies >80% for short tubes (e.g. 800 MHz < 2 m)

Disadvantage: still a high number of cavities

HEIKA collaboration

CERN initiative

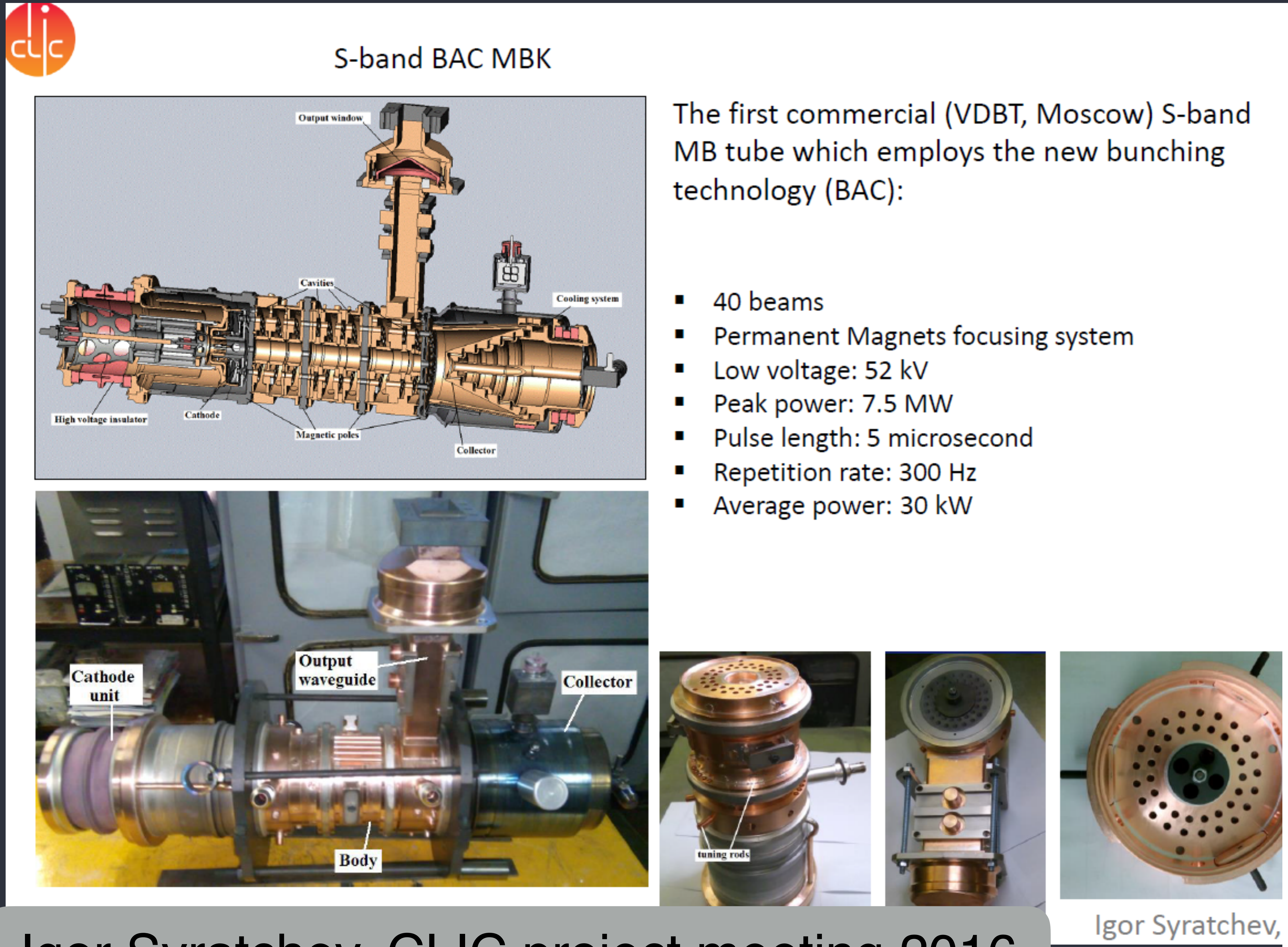
High Efficiency International Klystron Activity (HEIKA)

- Evaluation and testing of the different optimisation methods.
- Close collaboration between institutes and industry.
- Optimise for efficiency rather than peak power.

HEIKA: CERN, SLAC (USA), Lancaster University (UK), Cockroft Institute (UK), Thales Group, L3, ESS (SE), Moscow University of Finance & Law (RU), VDBT (RU), …

BAC PoP test

I. Guzilov, VDBT



S-band BAC MBK

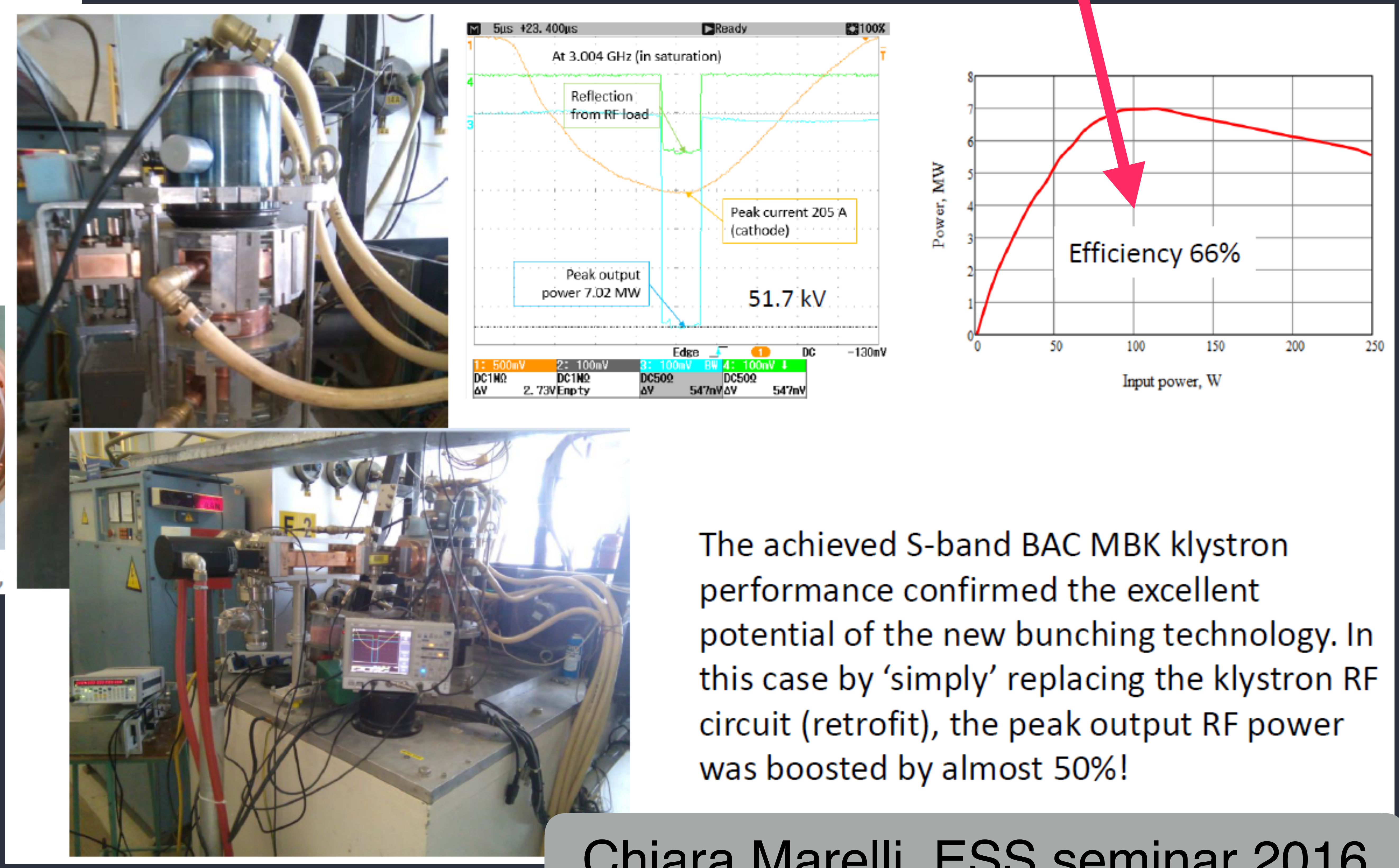
The first commercial (VDBT, Moscow) S-band MB tube which employs the new bunching technology (BAC):

- 40 beams
- Permanent Magnets focusing system
- Low voltage: 52 kV
- Peak power: 7.5 MW
- Pulse length: 5 microsecond
- Repetition rate: 300 Hz
- Average power: 30 kW

Igor Syratchev,

Igor Syratchev, CLIC project meeting 2016

- original efficiency 42%
- tested efficiency: 66%



The achieved S-band BAC MBK klystron performance confirmed the excellent potential of the new bunching technology. In this case by ‘simply’ replacing the klystron RF circuit (retrofit), the peak output RF power was boosted by almost 50%!

Chiara Marelli, ESS seminar 2016

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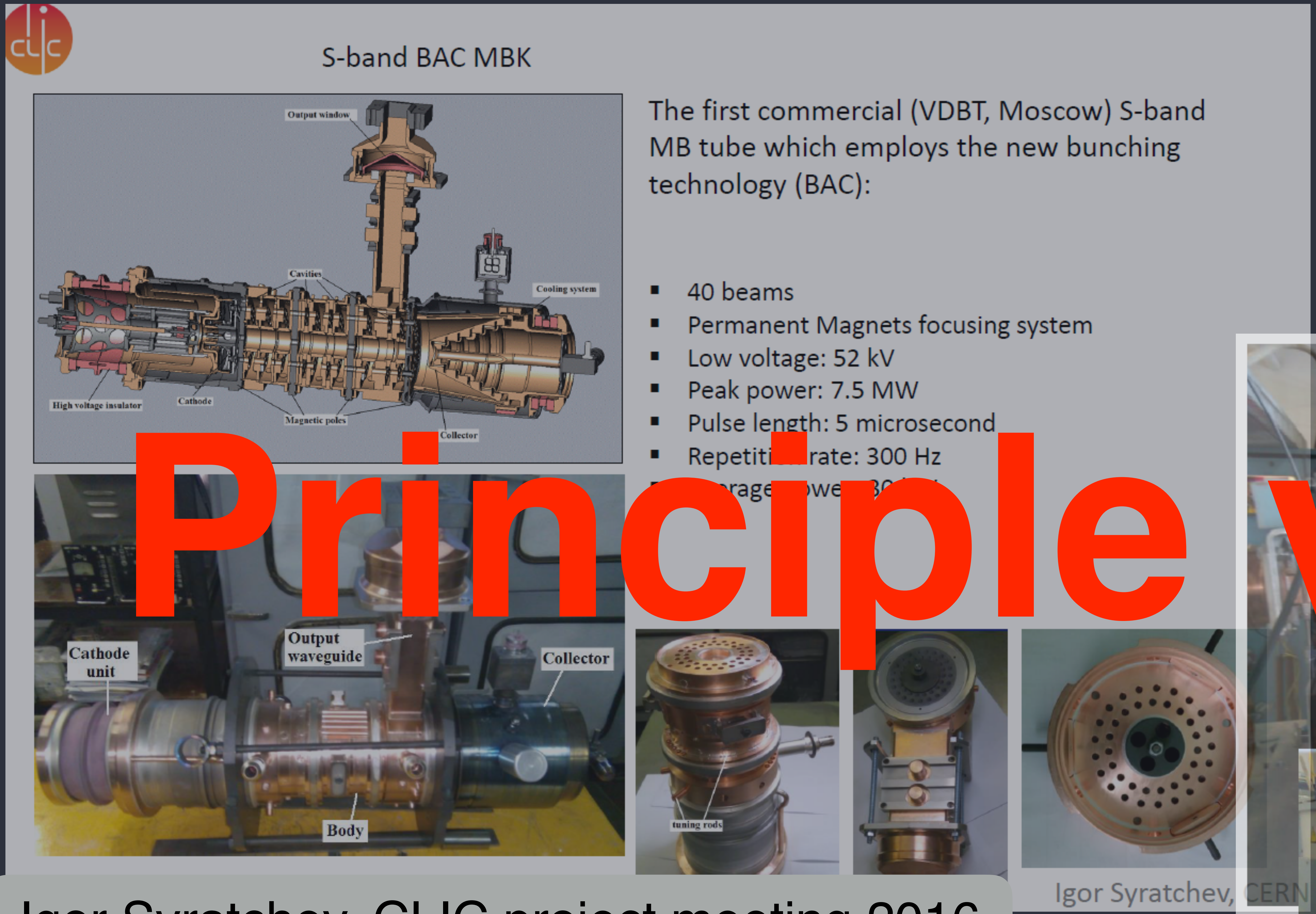
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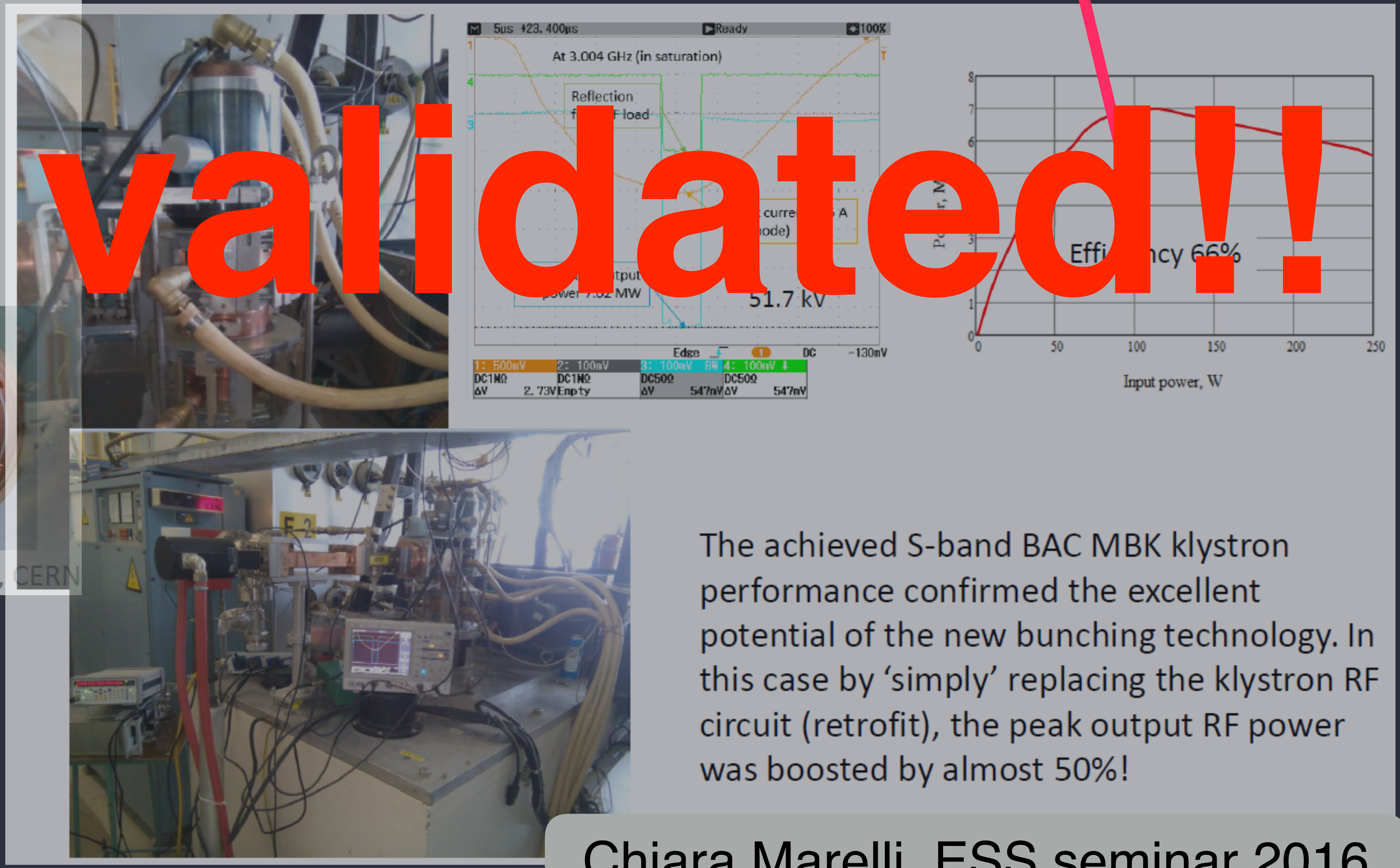

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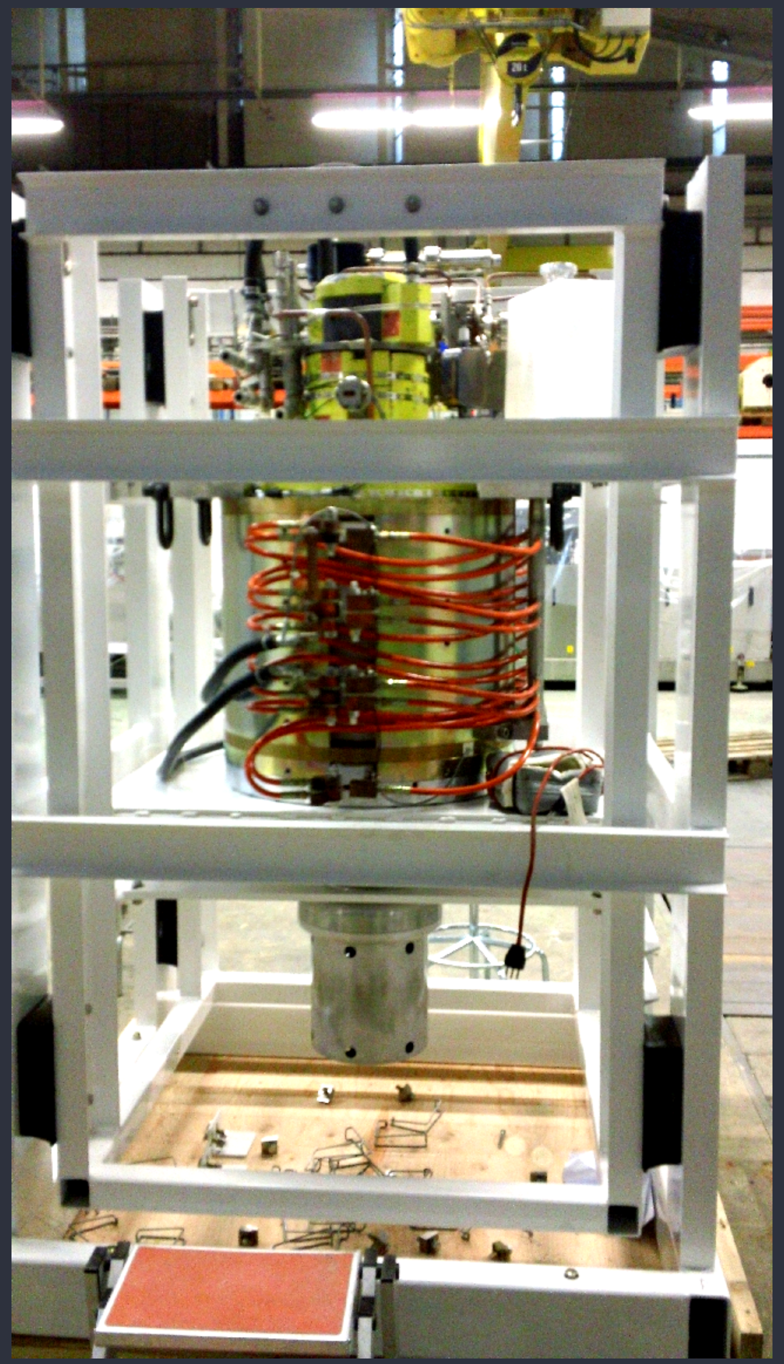
Principle validated!!

Chiara Marelli, ESS seminar 2016

XBOX 1-2: high peak power

CERN development

2 X-band test stands for testing of high-gradient accelerating structures at CERN

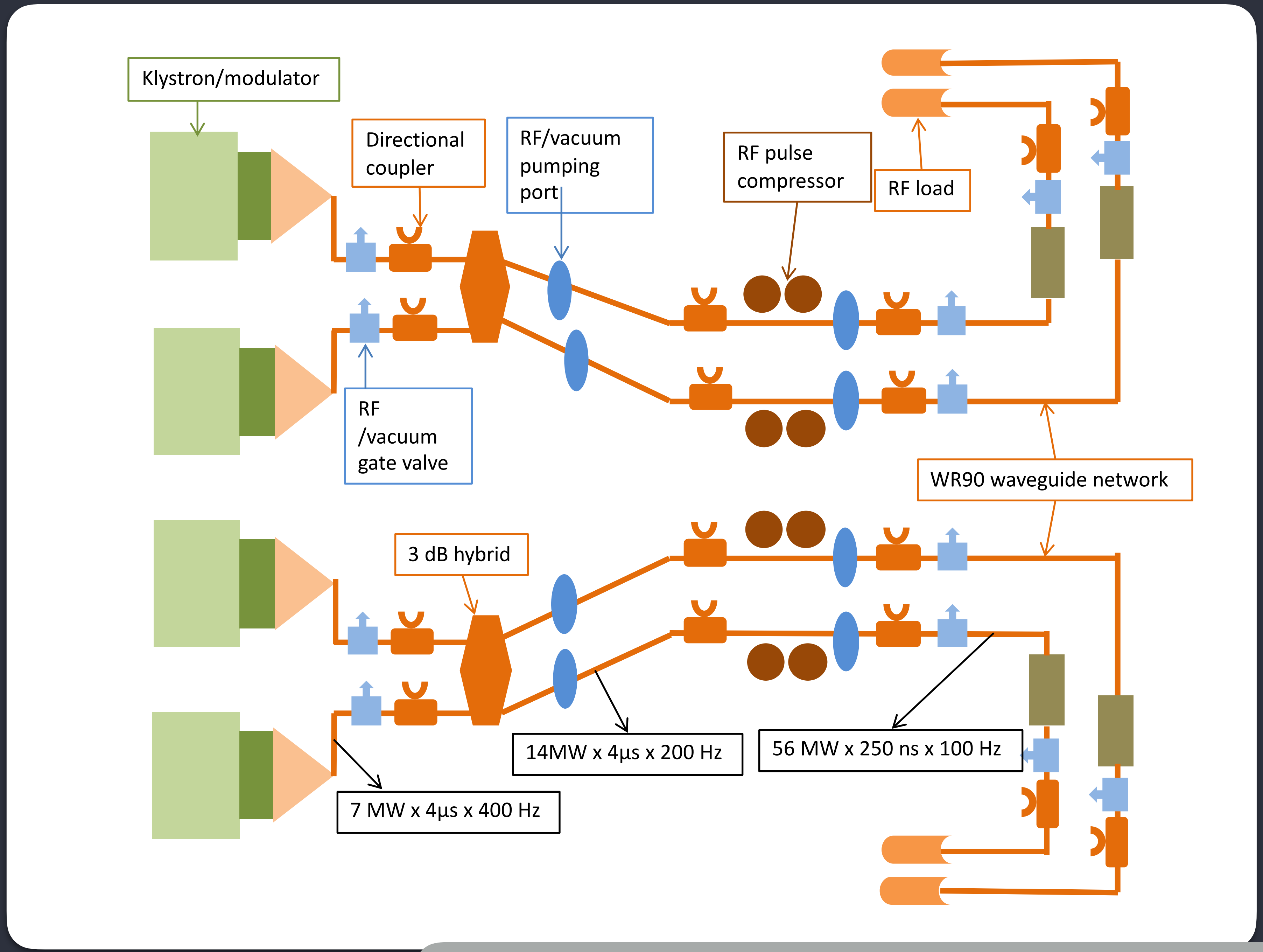


- Using two CPI 50 MW, 1.5 μs, 50 Hz klystrons (410 - 470 kV), based on the XL5 klystron developed in SLAC, CERN, PSI, Trieste collaboration (2008 - 2010) + Scandinova modulator.
- After pulse compression: 140 MW, 250 ns

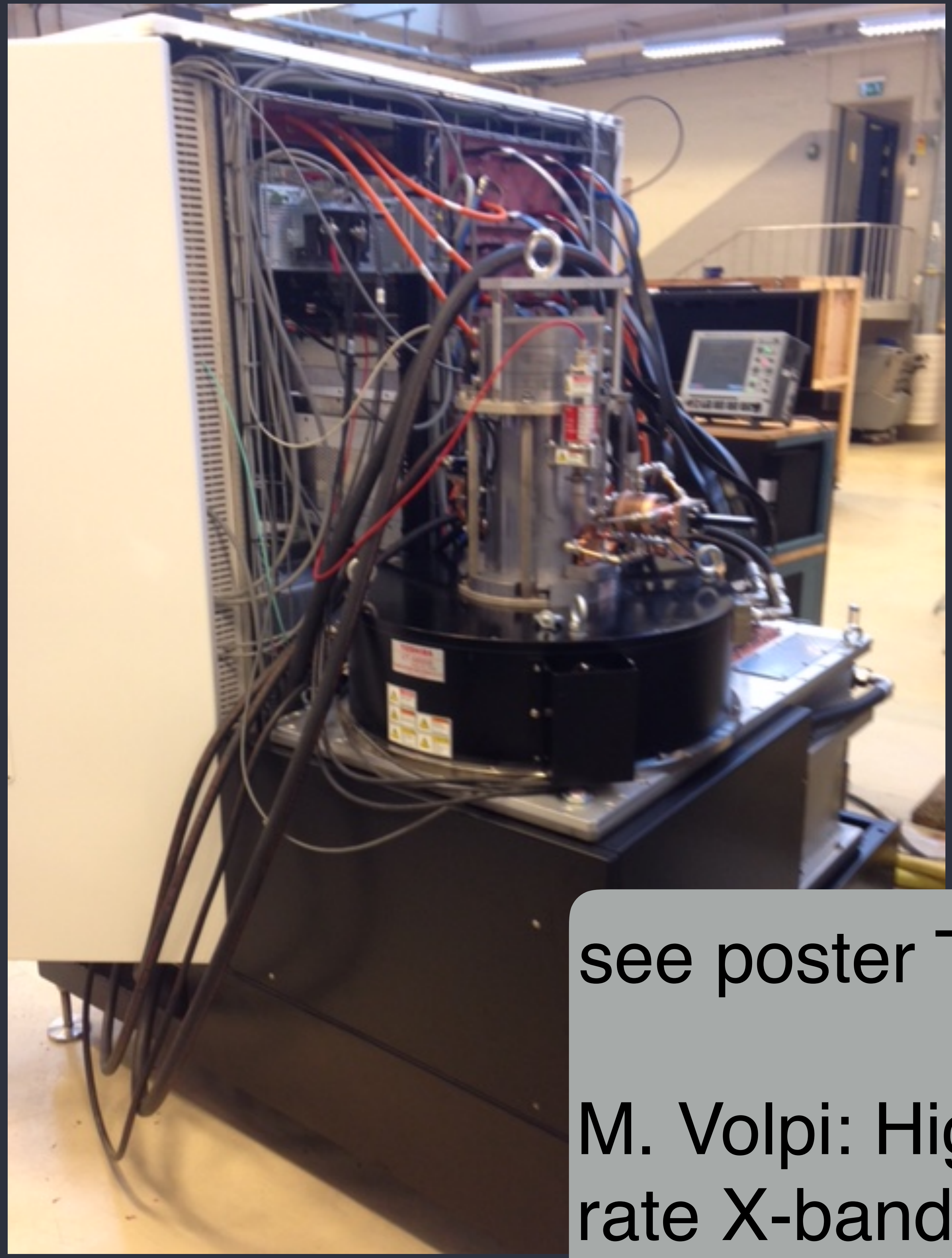
XBOX 3

CERN development

- provides 4 new test places with 45 MW running at 200 Hz repetition rate by combining 2x2x6 MW klystrons (Toshiba E37113)



B. Woolley, CLICWS 2016



see poster THPMK104 on Thursday:

M. Volpi: High power and high repetition rate X-band power source using multiple klystrons

Klystrons summary

1) Large gain: simple solid state pre-amps in ~100 W range.
2) High output power in the MW range.
3) Frequency reach into X-Band.
4) Long lifetime, typically around 40 kh.
5) Only choice for high power at high frequencies.

1) HV needed, mostly > 100 kV: oil tanks, expensive modulators, …
2) Gain curve saturates at full power: operation usually below saturation at reduced efficiency.

Klystrons summary

Type	Gain [db]	$P_{out, pulsed}$ [MW]	$P_{out, CW}$ [MW]	V_{input} [kV]	T_{pulse} [ms]	$T_{rise/fall}$ [ns]	efficiency DC to RF [%]	frequency [GHz]
Single beam	~40-45	0.3 - 3	1.2	90 - 450	< 4	300	55	0.3 - 15
Multi beam	~40-45	10 - 50	1.2	90 - 450	< 4	300	60	0.3 - 15
Future SB	same	higher	higher	50% lower	tbd	similar	70 - 80	same
Future MB	same	higher	higher	50% lower	tbd	similar	70 - 80	same

- Basically the only RF source type providing multi-MW output power (peak) up to X-band.
- Rise time determined by the modulator: 100 - 300 us.

Development: Vigorous R&D program promises to:

i) increase efficiency at working point up to 70% (single beam), or 80% (multi beam),
ii) lower HV requirements (no oil tanks),
iii) shorter tubes,
iv) more W/$

- Further gains by using permanent or SC magnets and advanced LLRF.

Gridded tubes

First (non-gridded) tubes by J.A. Fleming, patented 1904

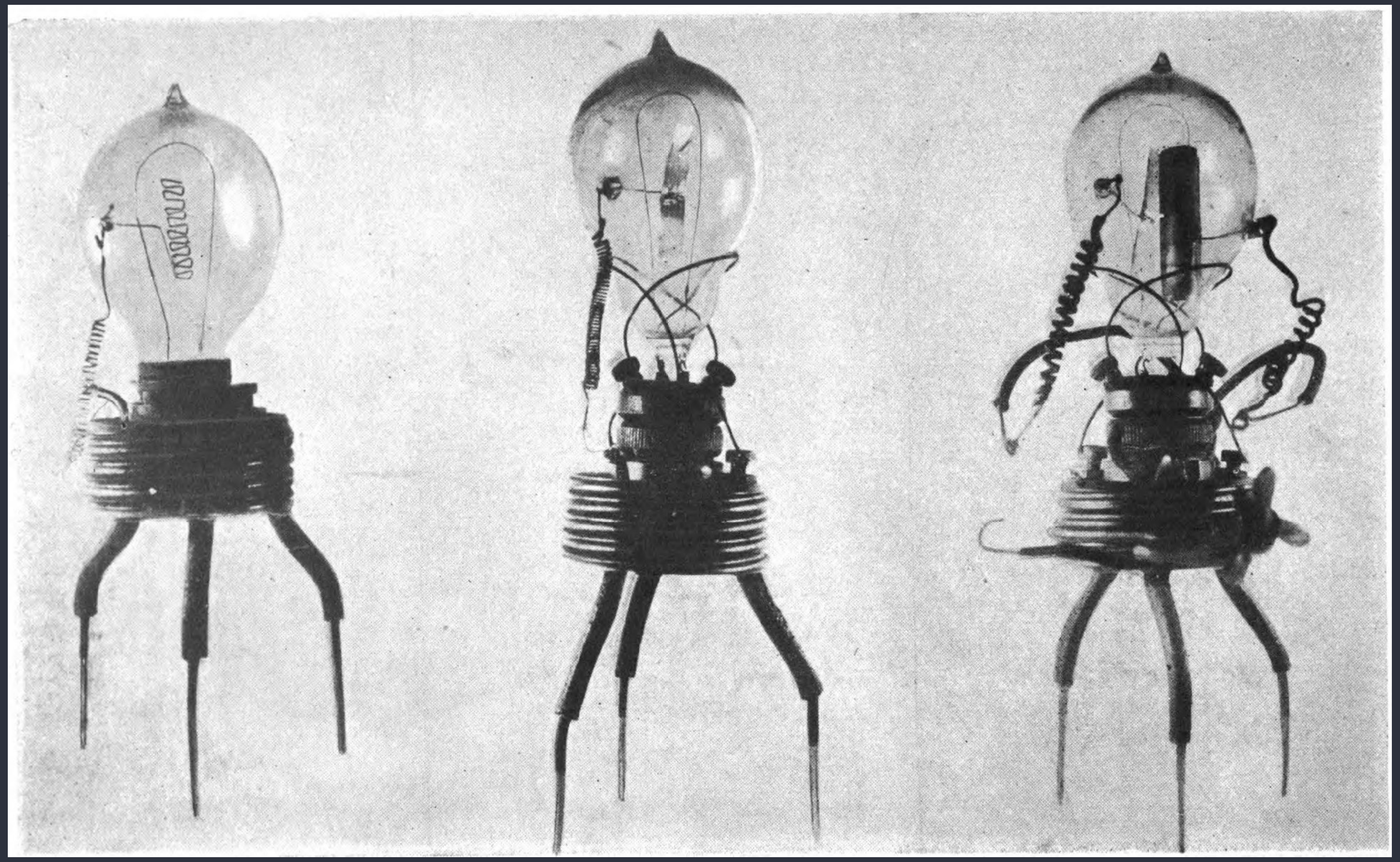
First tube: Diode

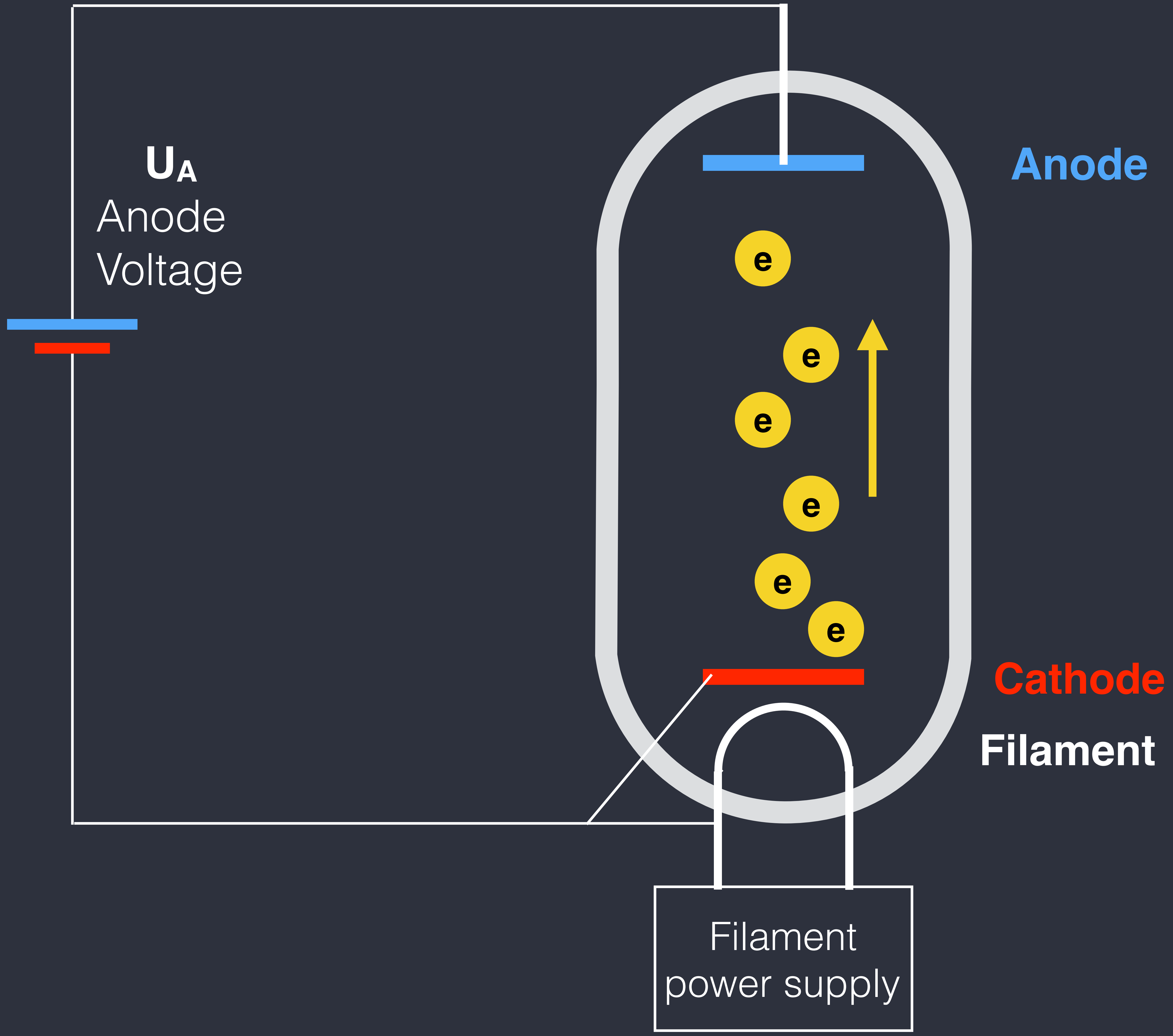
Diode: (without a grid)

(1) Thermionic emission of electrodes,

(2) Electrodes are attracted by the anode:

current flow





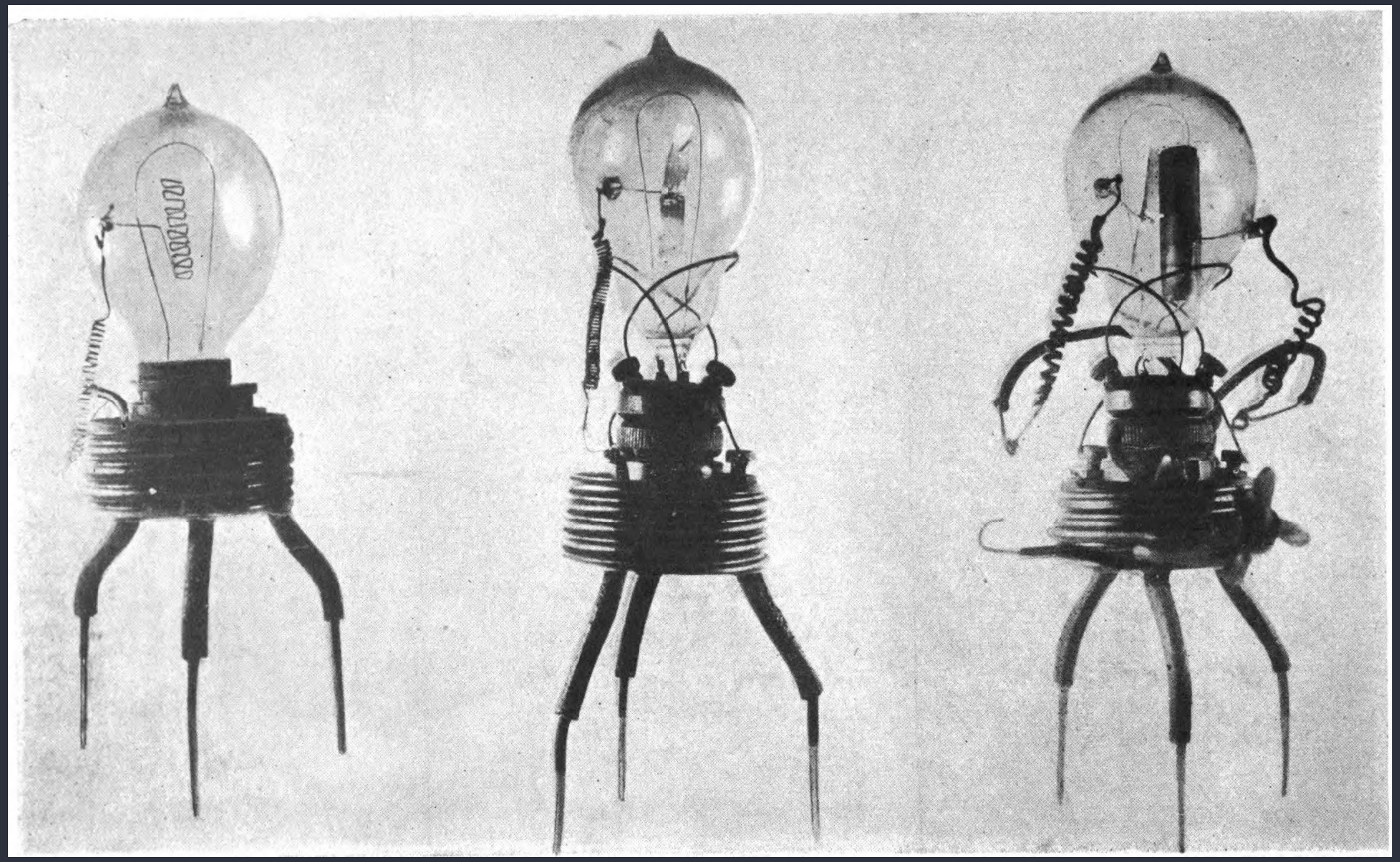
Frank Gerigk, IPAC18, Vancouver, Canada, 30 April 2018

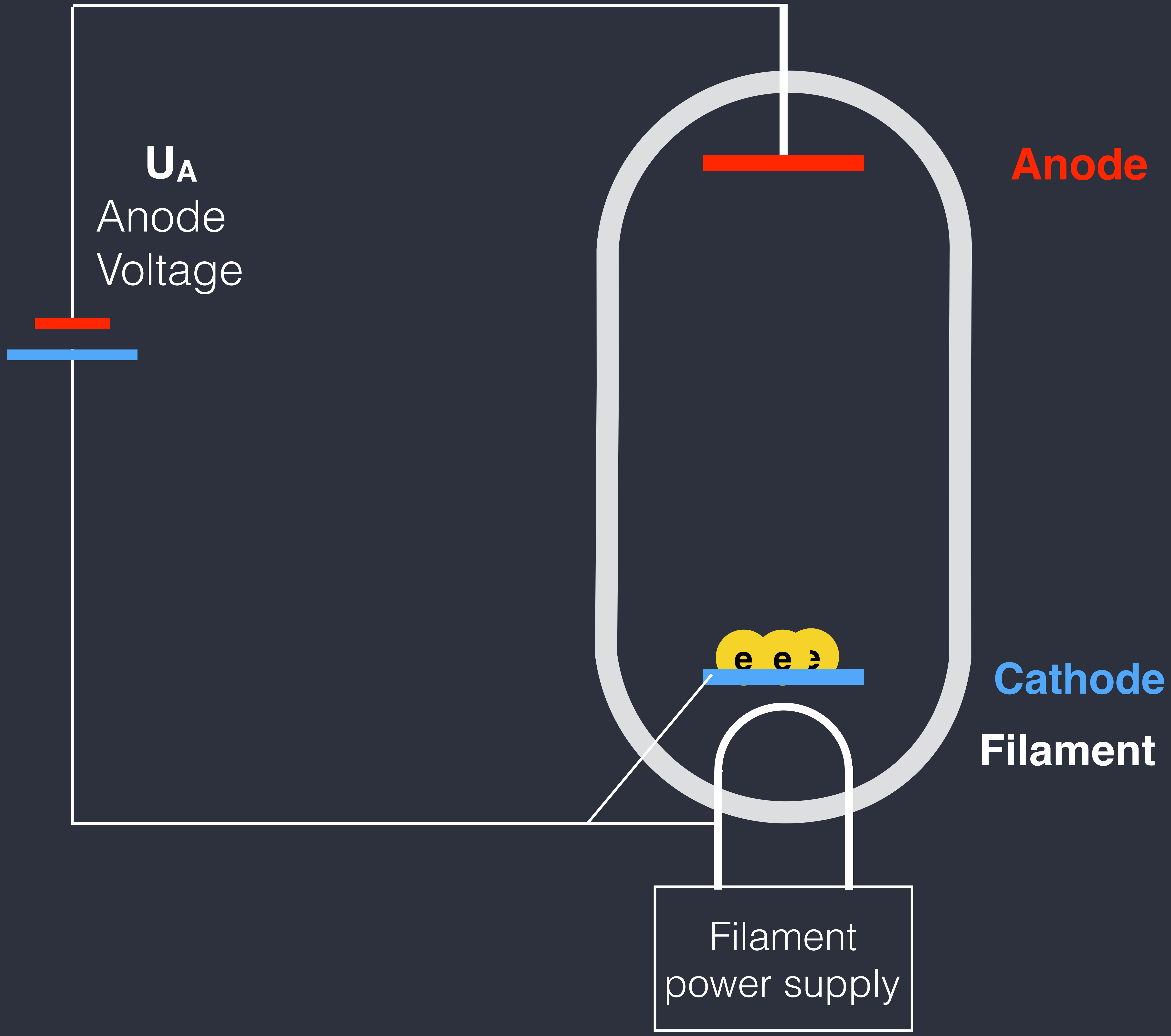
First tube: Diode

Diode: (without a grid)

(1) Thermionic emission of electrodes,

(2) Changing the voltage: **no current**





Gridded tubes: Triode

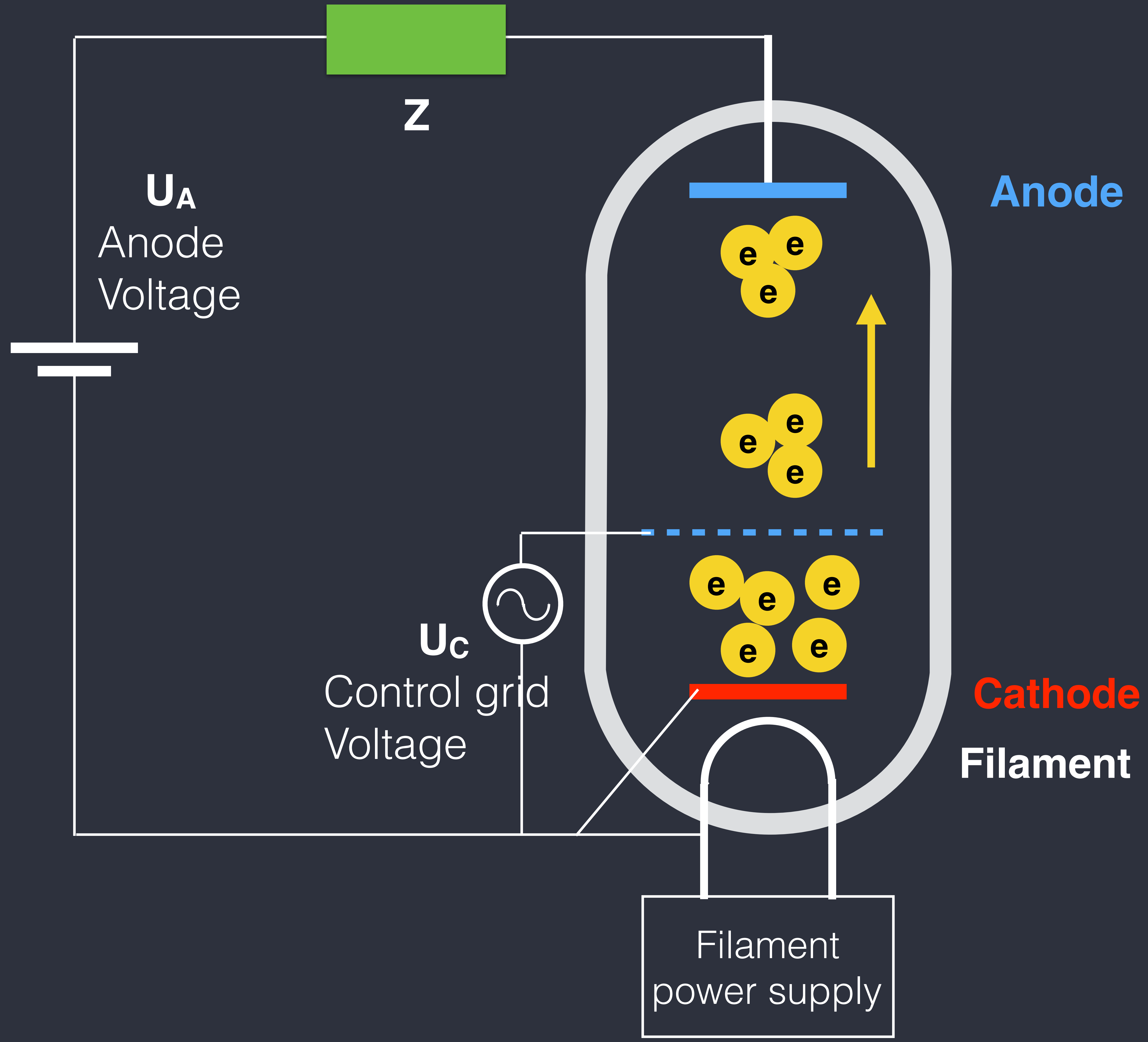
Triode:

(1) Thermionic emission of electrodes.

(2) Electrodes are attracted by the anode: current flow.

(3) Modulating the grid voltage modulates the electron flow and therefore the anode current.

(4) Placing a resistive load in the anode circuit will produce a modulated, amplified voltage.



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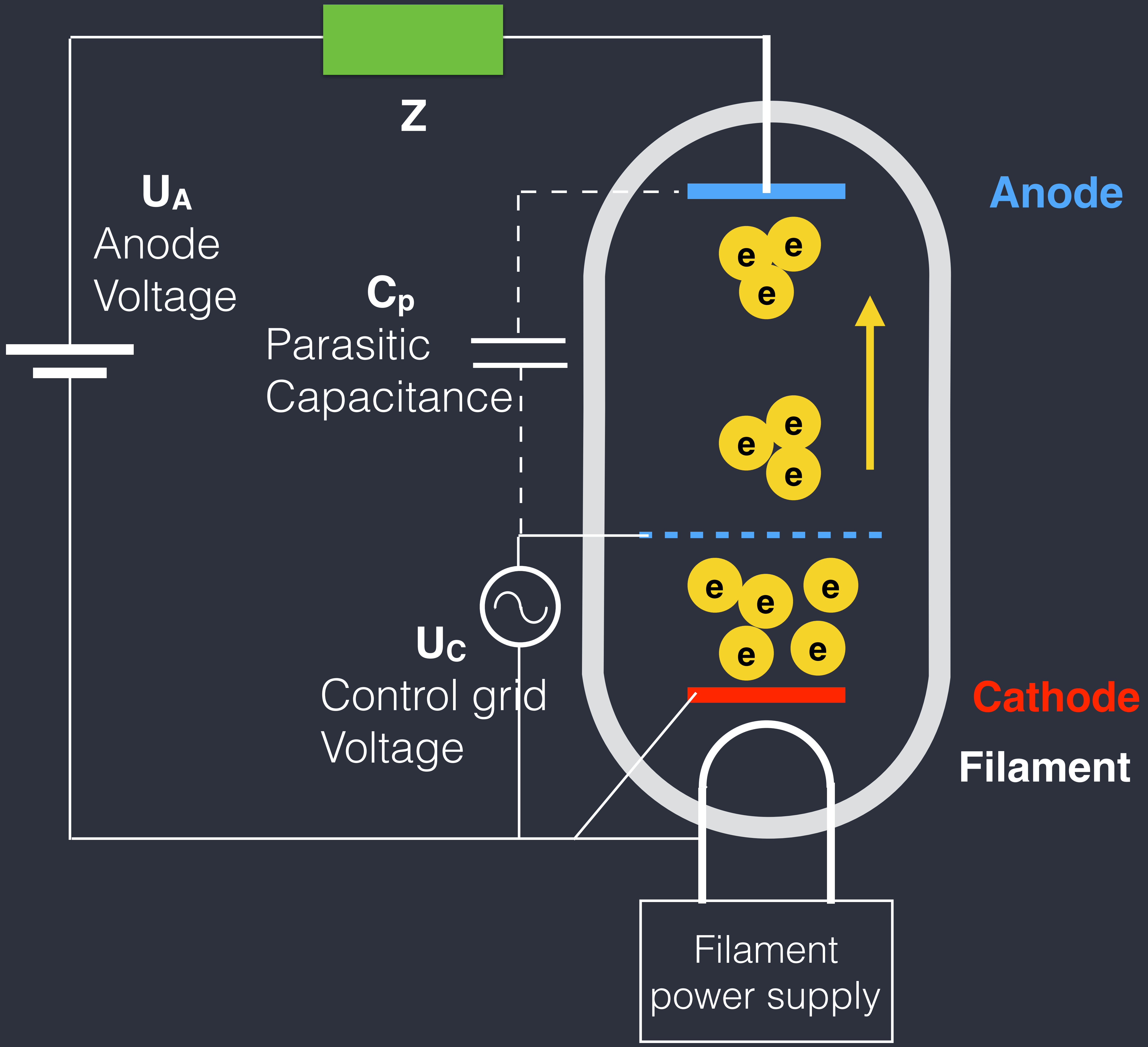


Parasitic capacitance can cause oscillations, especially with inductive loads.

Gridded tubes: Tetrode

Tetrode:

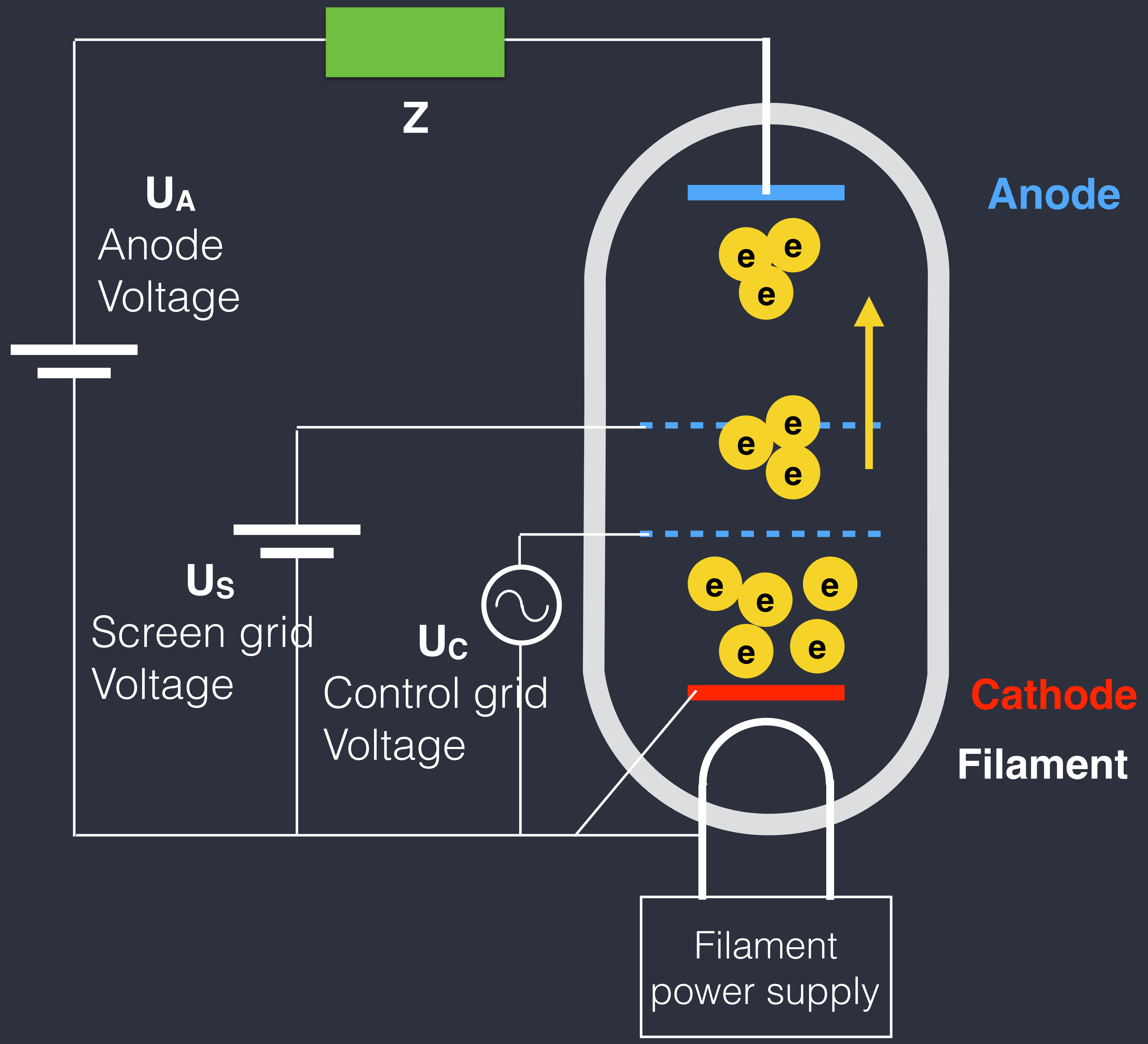
(1) Thermionic emission of electrodes.

(2) Electrodes are attracted by the anode: current flow.

(3) Modulating the grid voltage modulates the electron flow and therefore the anode current.

(4) Placing a resistive load in the anode circuit will produce a modulated, amplified voltage.

(5) A screen grid decouples the control grid from the anode: i) reduces oscillations with inductive loads, ii) increases gain.



Tetrodes pros/cons

1) High output power up to 4 MW.
2) High efficiency up to 70%.
3) Very robust and reliable.

1) Limited frequency range (< 400 MHz).
2) Limited gain: 2-3 stages of amplification needed for MW-class.
3) Small market, tubes go out of production.
4) Few companies are able to build tetrode-based amplifiers.

Diacrodes®

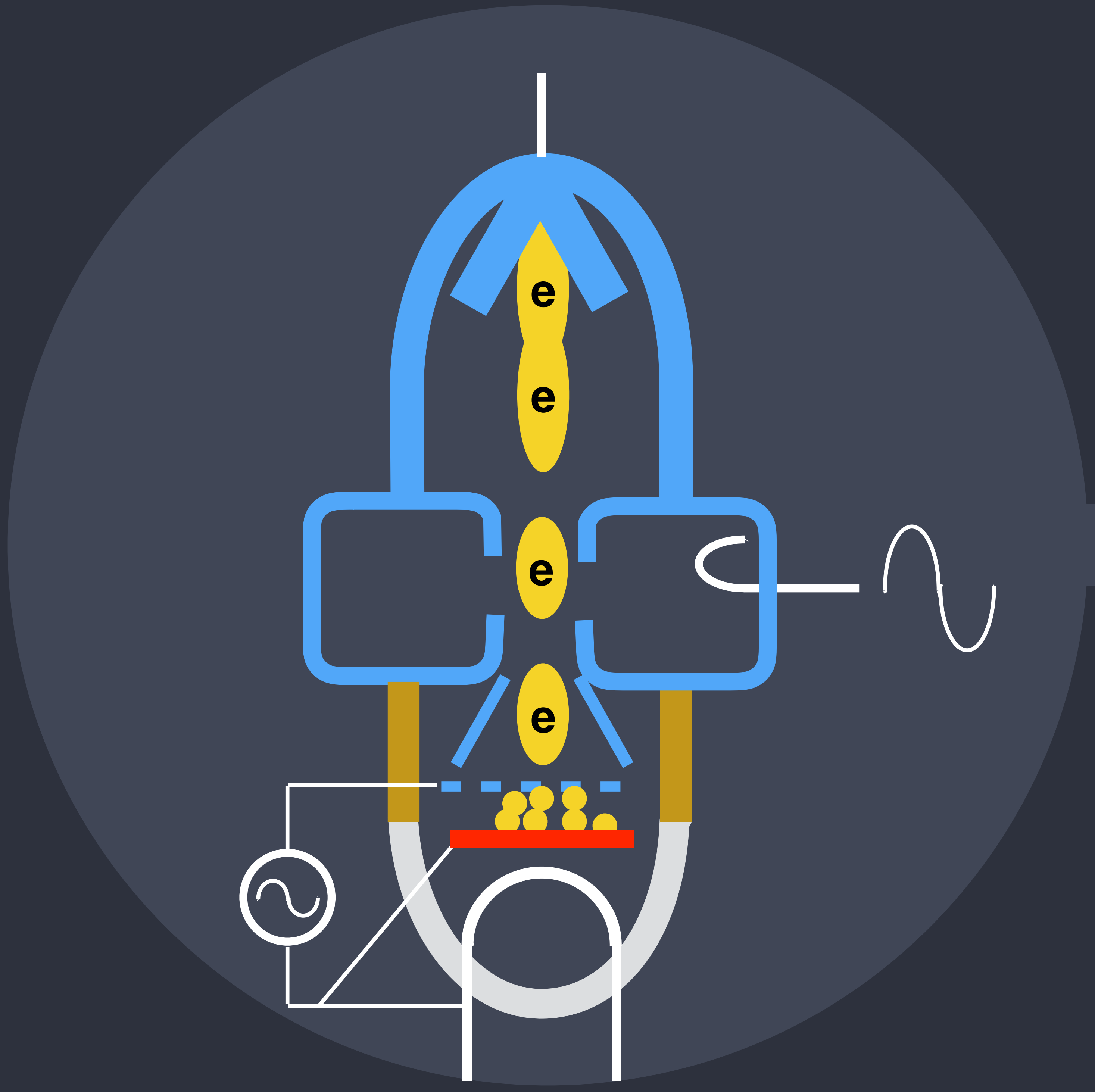
State of the art, developments

Only new development in the last decade: improved Tetrode by Thales: Diacrode®

- Minimising reactive currents in cathode and grid meshes allows to:
  - i) double the power at a given output frequency, or
  - ii) double the frequency for a given output power
- Successfully operating at LANL since 2015.

State of the art:

Type	Gain [db]	$P_{out,\ pulsed}$ [MW]	$P_{out,\ CW}$ [MW]	V_{input} [kV]	T_{pulse} [ms]	$T_{rise/fall}$ [ns]	efficiency DC to RF [%]	frequency [MHz]
Tetrode	~15	4	1.5	10 - 25	any	ns	70	30 - 400
Diacrode®	~15	3	2	20 - 30	any	ns	70	30 - 400



Inductive Output Tubes

- Invented in 1938 by A.V. Haeff
- Mixing a klystron with a gridded tube, also called klystrode

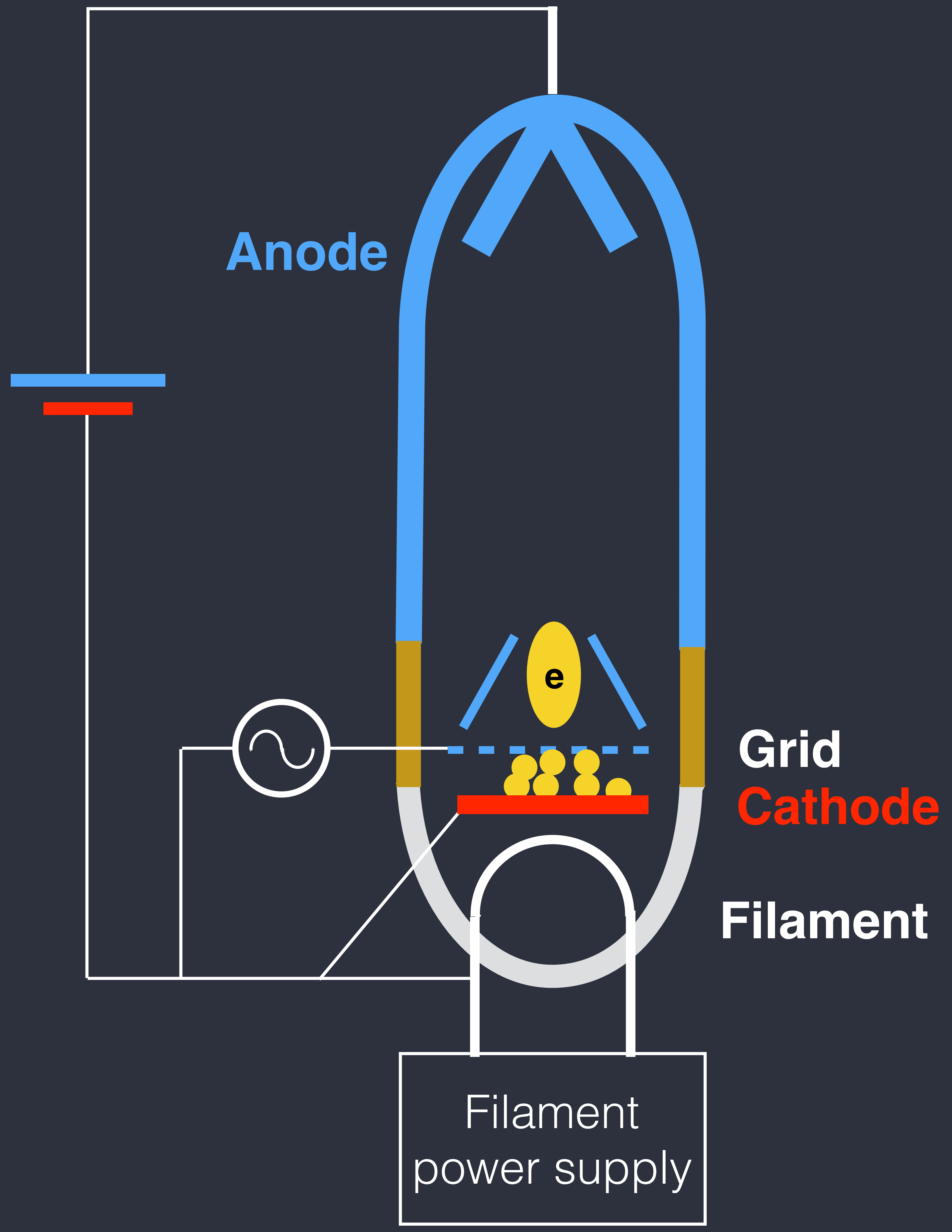
Inductive Output Tubes (IOT)

Triode input

(1) Heat the cathode ➜ release of electrons.

(2) Electrons are accelerated towards the anode (blue part of the tube).

(3) The grid modulates the electron current into bunches.



Inductive Output Tubes (IOT)

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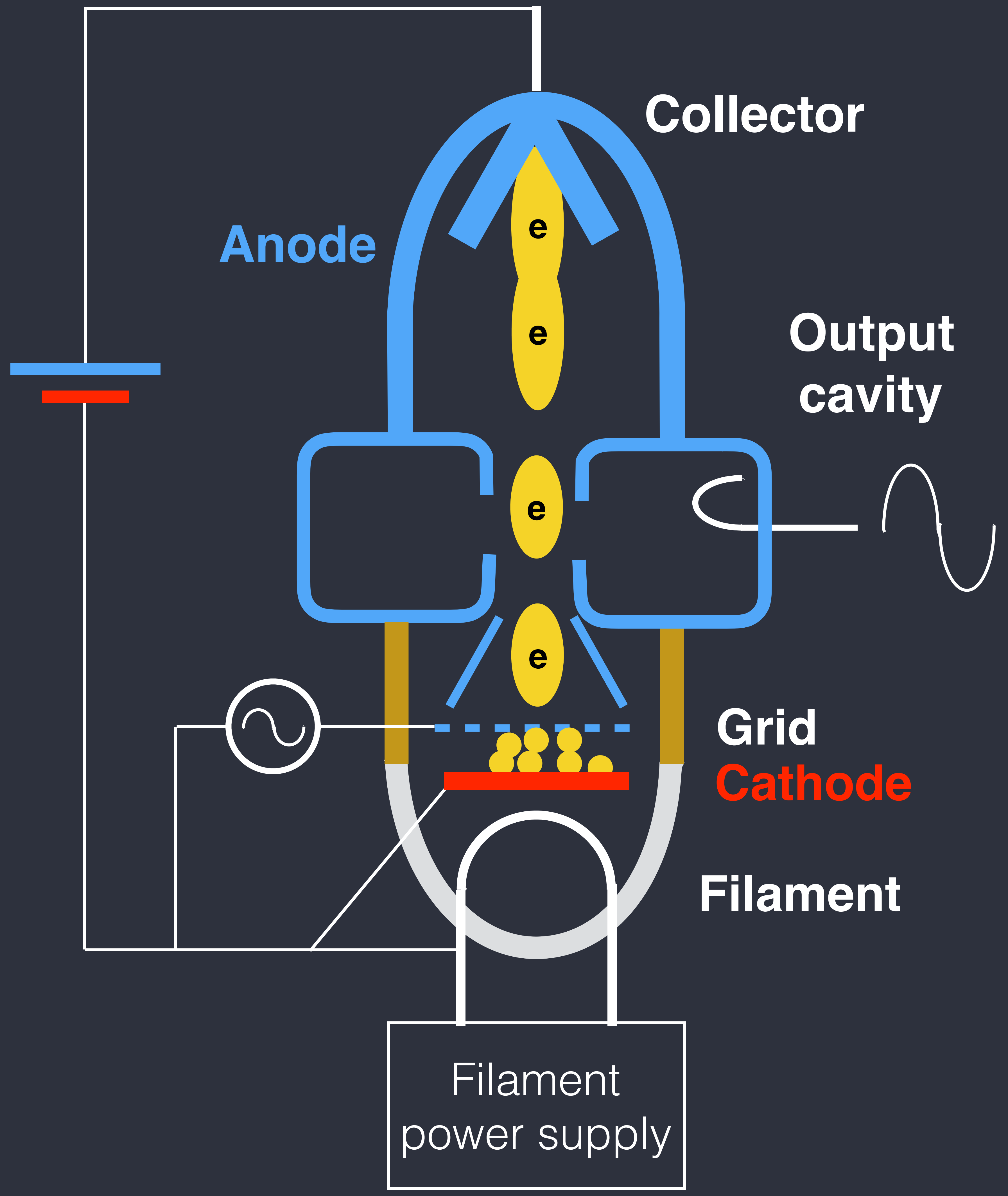
Klystron output

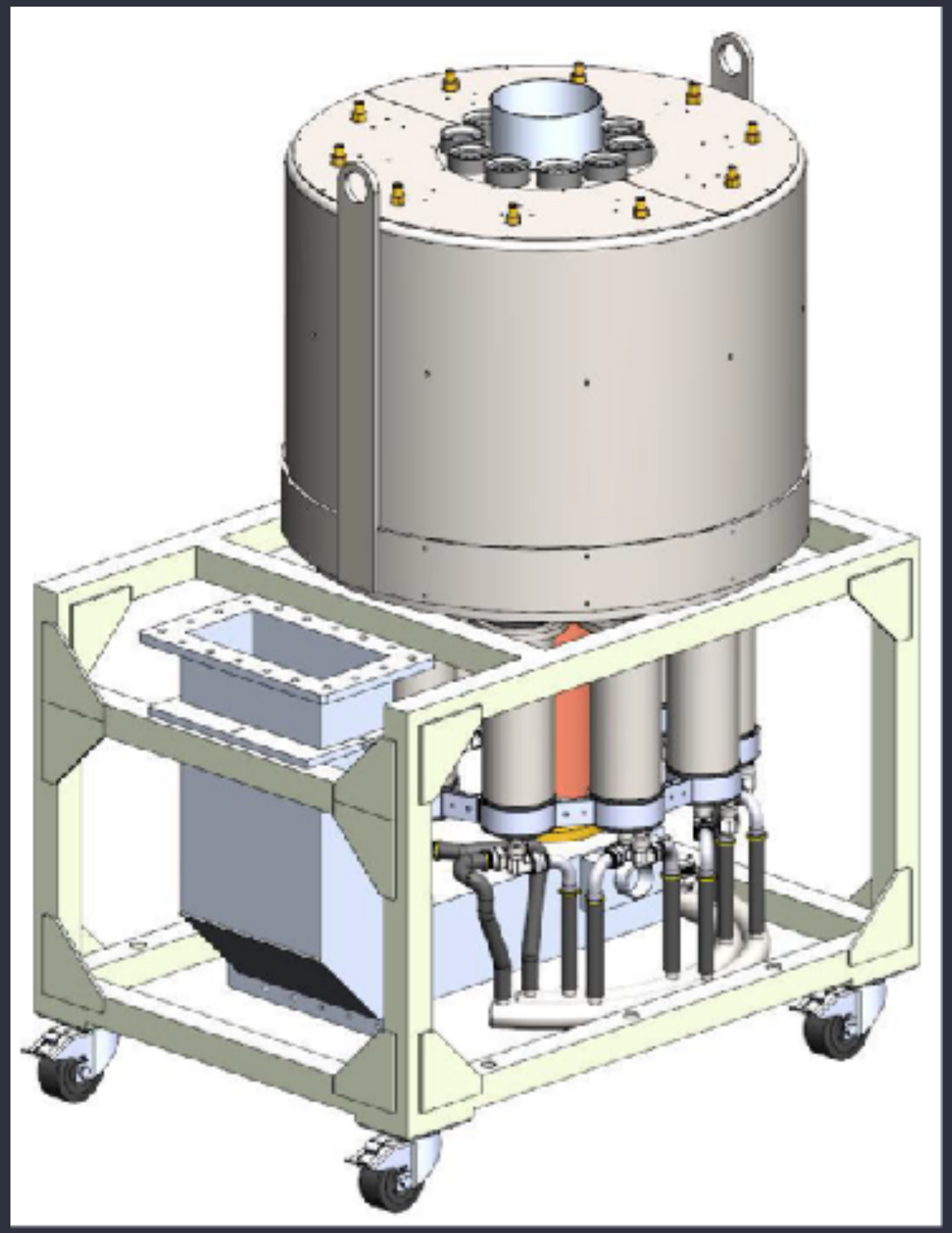
(4) Bunches excite resonant fields in the output cavity, which are then extracted.

(5) The slowed-down bunches are collected.



Development: MB-IOT

- Development launched by ESS to have an alternative to 704 MHz MW-class klystrons.
- Higher efficiency than standard klystrons (DC to RF: ~70%) but (for now) higher initial cost.
- ESS ordered two 1.3 MW MB-IOTs (3.5 ms, 14 Hz) at **Thales/CPI** and **L3**.
- Extensive testing in 2017 at CERN, which contributed with a dedicated test stand.

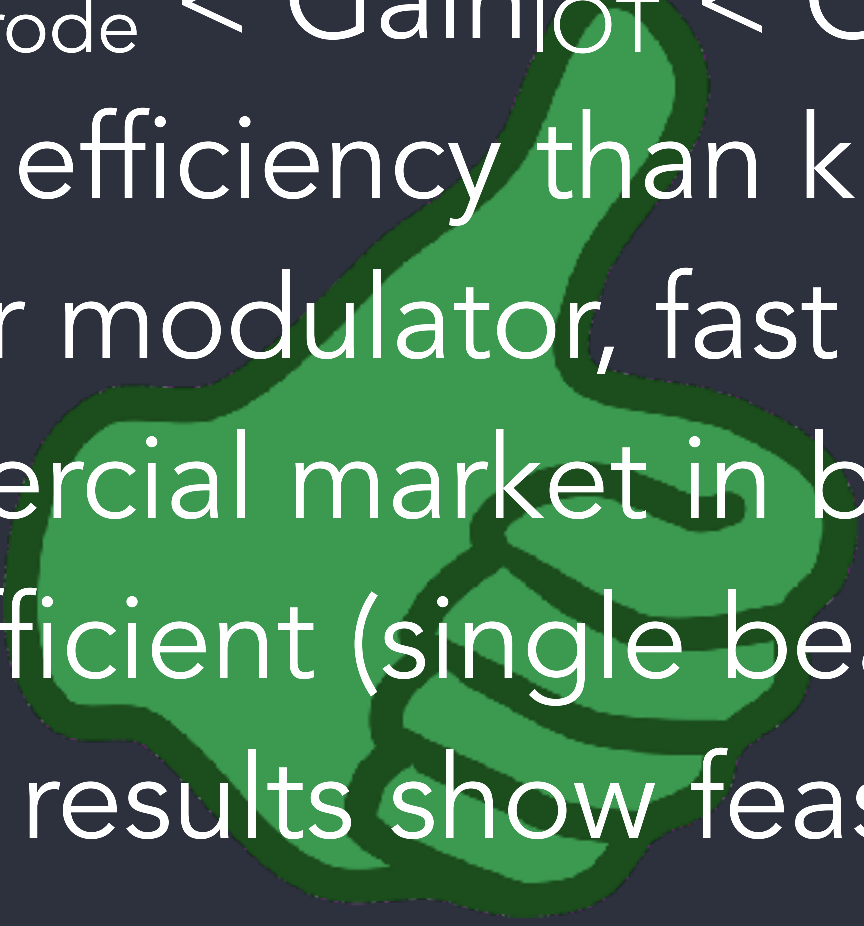
THALES ELECTRON DEVICES CPI

L3 communications

see talk WEXGBF1 on Wednesday:

M. Jensen: Testing of the ESS MB IOT prototypes

IOTs pros/cons



1) Higher frequencies than tetrodes.
2) $\text{Gain}_{\text{Tetrode}} < \text{Gain}_{\text{IOT}} < \text{Gain}_{\text{Klystron}}$
3) Higher efficiency than klystrons.
4) Simpler modulator, fast rise time.
5) Commercial market in broadcasting.
6) Cost efficient (single beam).
7) Recent results show feasibility of MB-IOTs.

1) Single beam units are limited to ~100 kW
2) MB-IOTs still need consolidation of R&D before larger scale production.

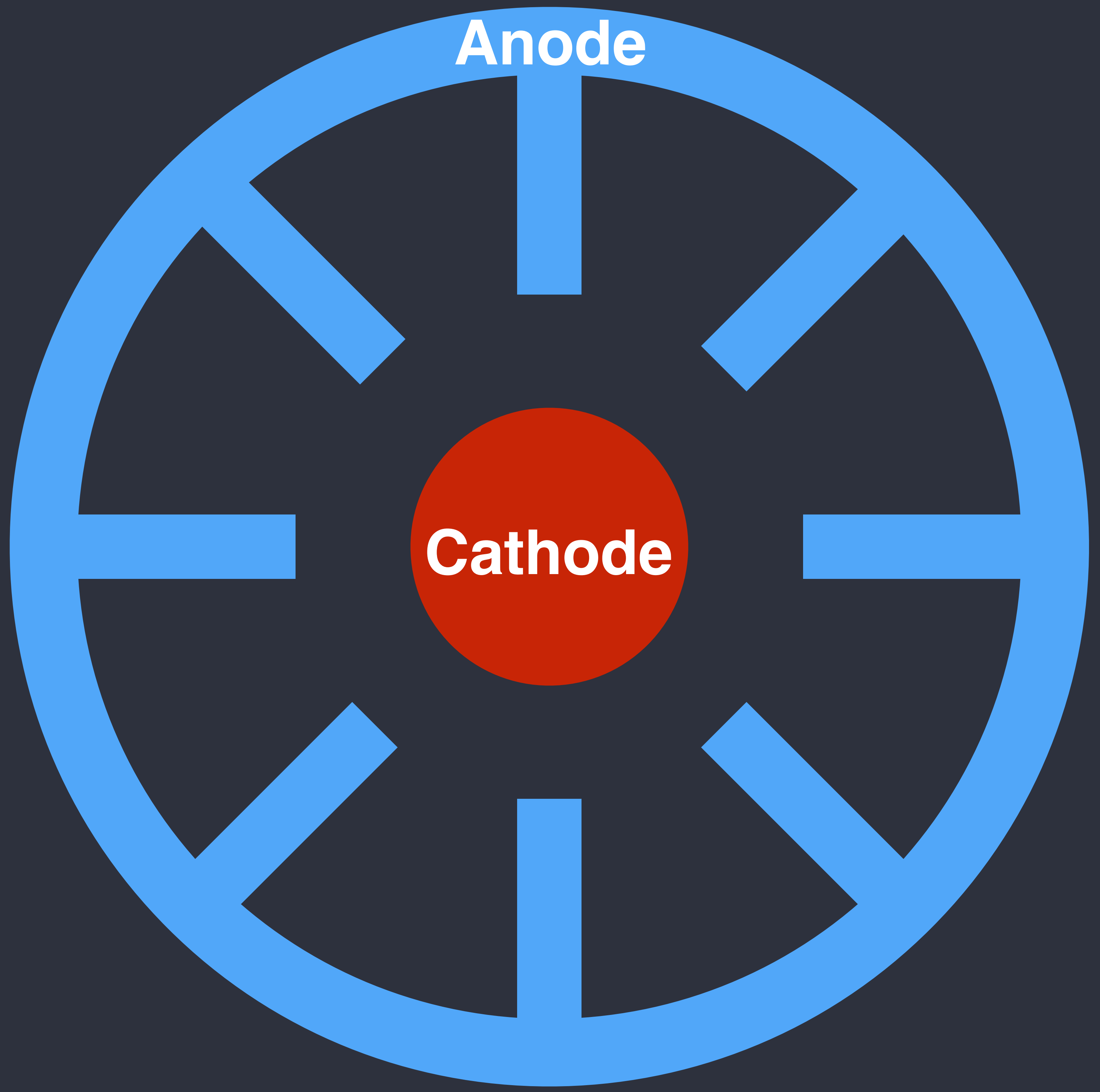
Type	Gain [db]	$P_{\text{out, pulsed}}$ [kW]	$P_{\text{out, CW}}$ [kW]	V_{input} [kV]	T_{pulse} [ms]	$T_{\text{rise/fall}}$ [ns]	efficiency DC to RF [%]	frequency [MHz]
single beam	20 - 23	130	85	36 - 38	any	ns	70	? - 1300
multi beam	20 - 23	1300	150	50	any	ns	70	704

Magnetrons

Invented in 1910 by H. Gerdien
Split anode design in 1920 by A. Hull
Built in Russia in 1937 by Alekseref & Malearoff

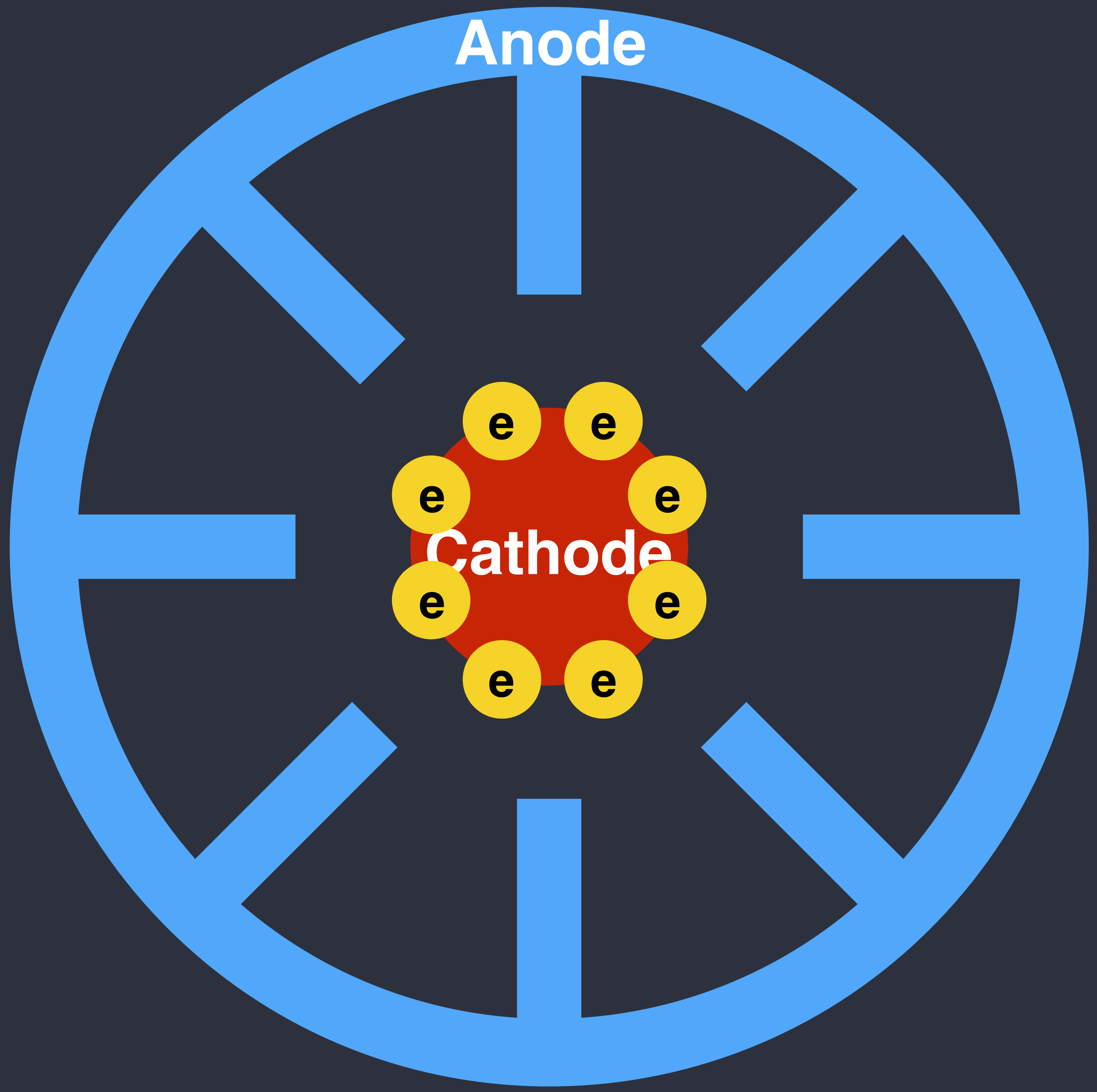
Cross section of a typical microwave cooker magnetron (courtesy: wikipedia)

Magnetrons



Magnetrons

(1) Heat the cathode ➜ release of electrons.



Magnetrons

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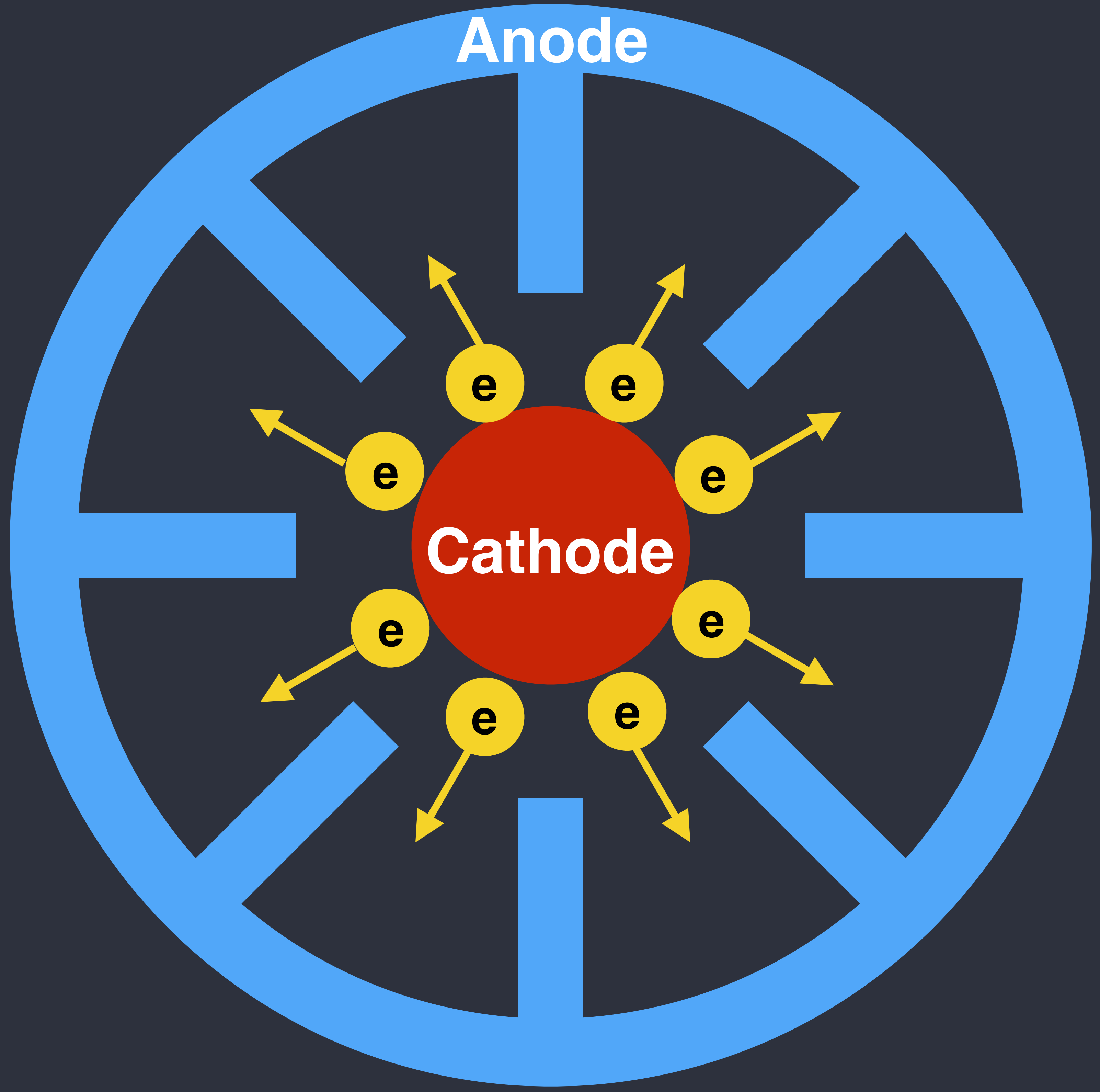
(2) Electrons are accelerated towards the anode.



Magnetrons

(1) Heat the cathode ➜ release of electrons.

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(3) The magnetic field makes the electrons rotate around the cathode

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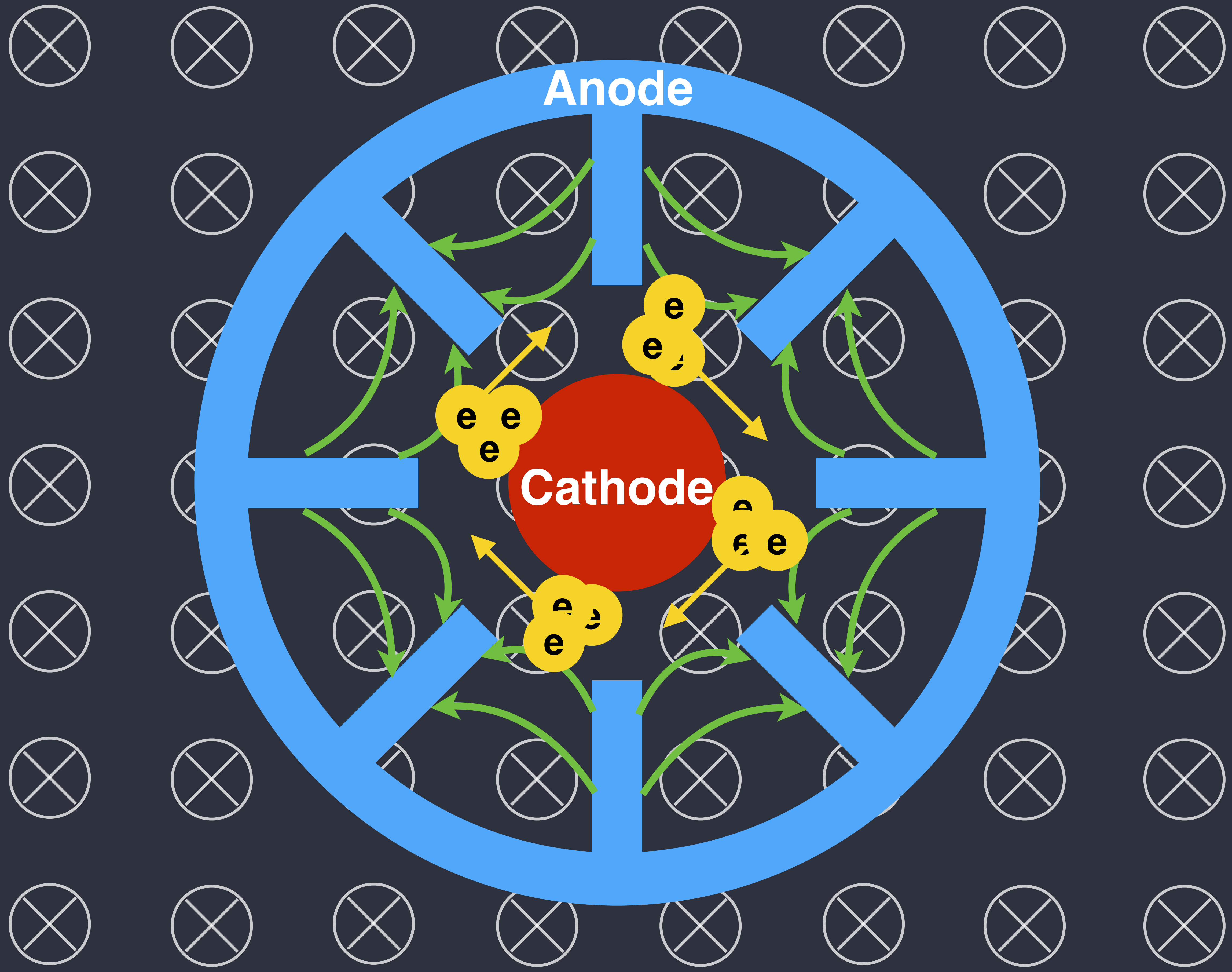
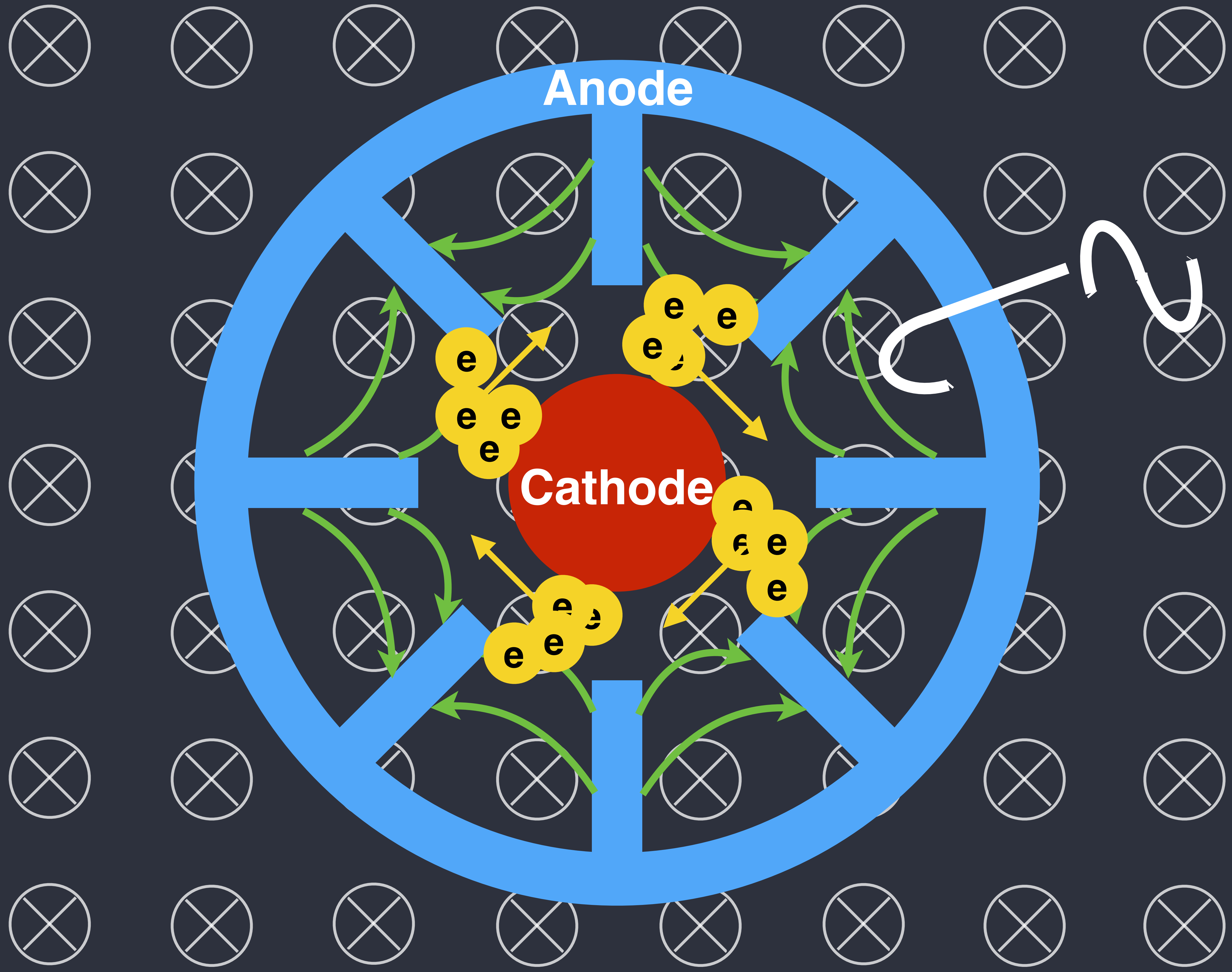
(4) RF fields in the cavities are excited by noise.

(5) The pi-mode in the cavities modulates the electron current ➜ the modulated current increases the cavity fields



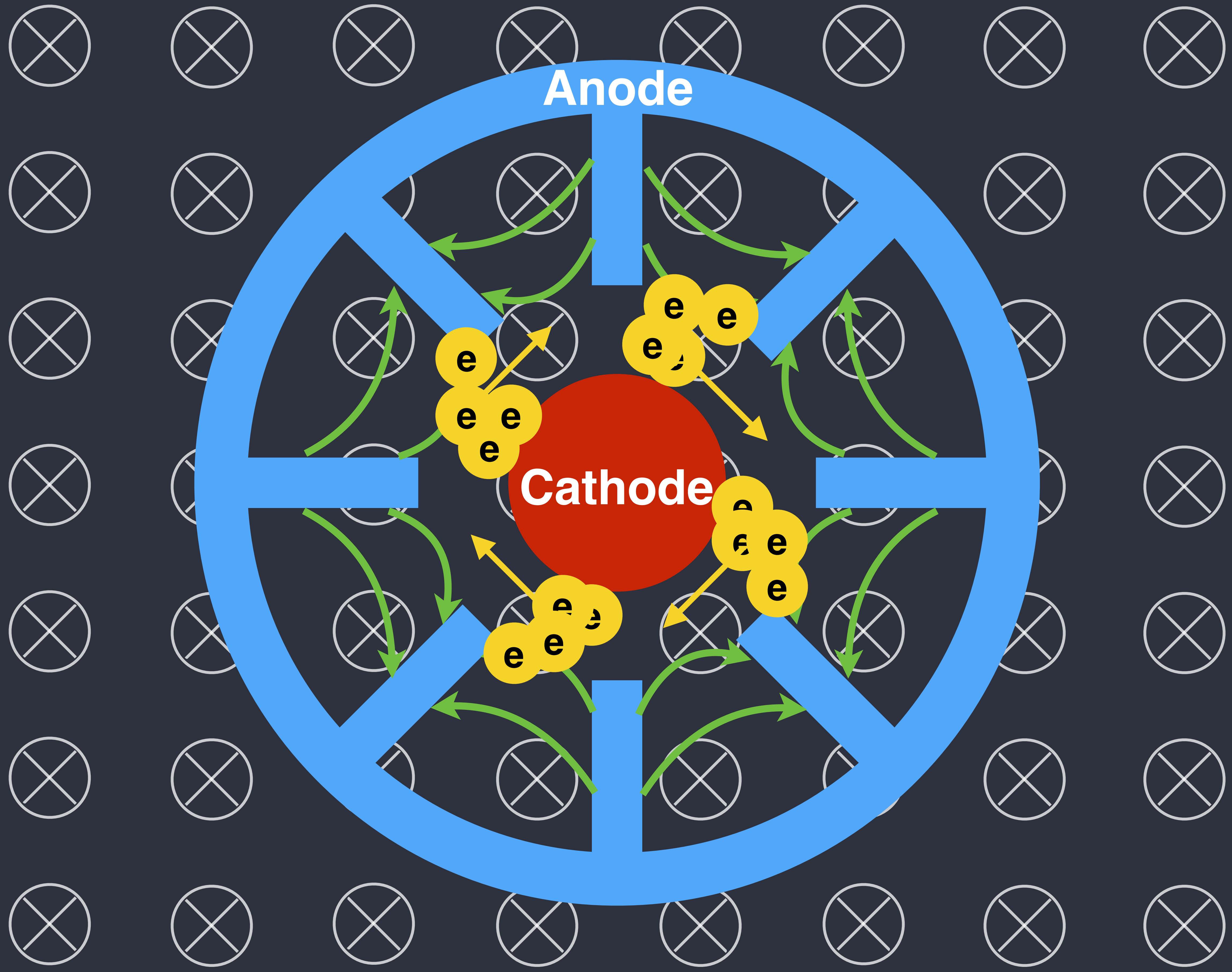
Magnetrons

(1) Heat the cathode ➜ release of electrons.
(2) Electrons are accelerated towards the anode.
(3) The magnetic field makes the electrons rotate around the cathode.
(4) RF fields in the cavities are excited by noise.
(5) The pi-mode in the cavities modulates the electron current ➜ the modulated current increases the cavity fields
(6) Power is coupled out from one of the cavities & electrons hit the anode: current flow



Magnetrons

- **Free running oscillator**: frequency is not stable enough to drive multiple phase-locked cavities.
- high efficiency, up to 90% for the tube alone.
- The use of stabilising control loops for the frequency + phase locking via injected RF has shown promising results in recent years.



Magnetrons pros/cons

1) Potentially high DC/RF efficiency of up to 85%.
2) Low price.
3) Good for single-cavity accelerators.

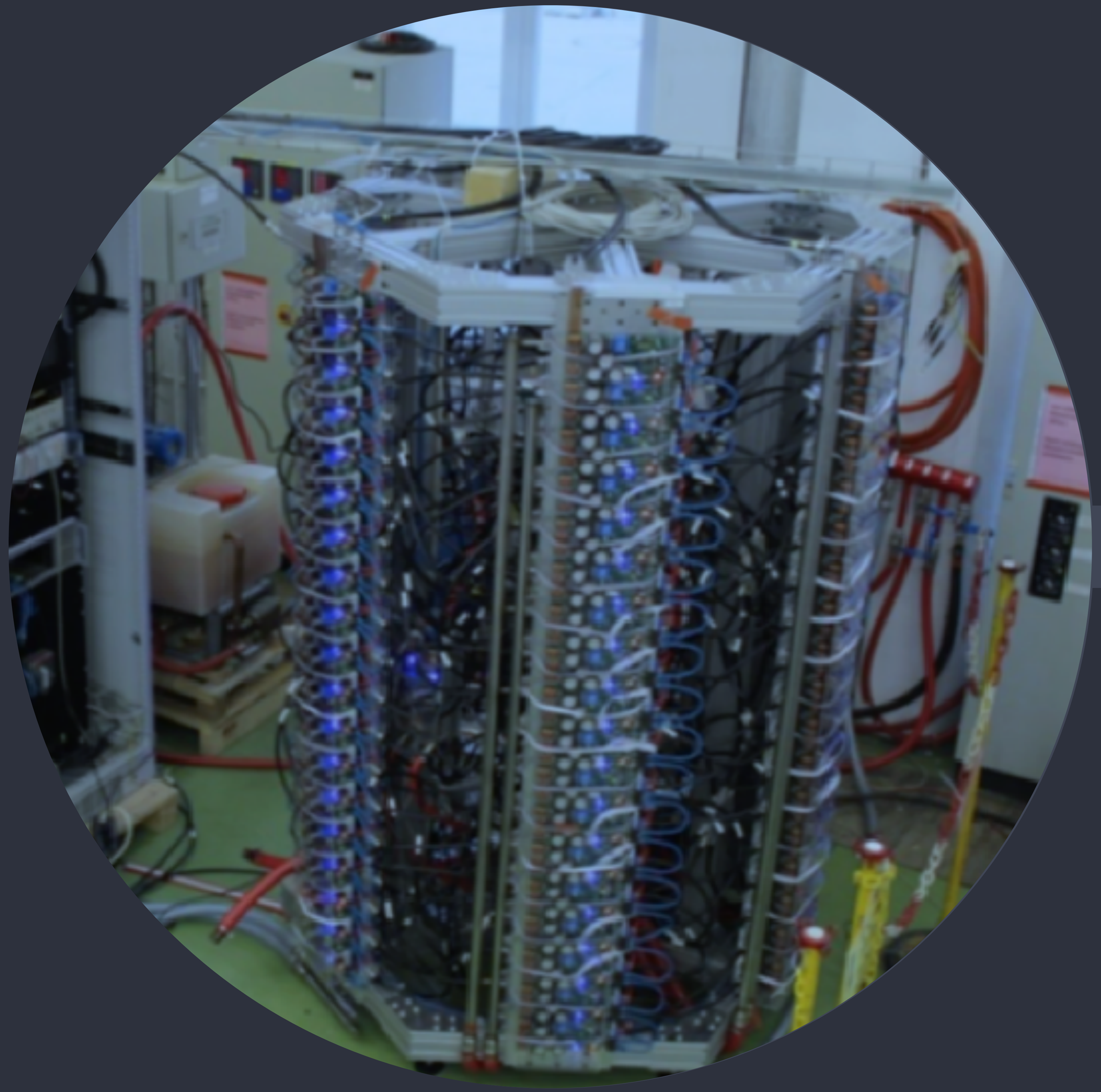
1) Difficult phase/amplitude regulation, further R&D needed to make them usable for multi-cavity accelerators.
2) Operation below working point may decrease efficiency considerably.
3) For now limited to ~100 kW.

Developments

- Proof of principle studies at Lancaster University & FNAL
  - i) Phase control of 1 magnetron, using 2 magnetrons with phase control gives amplitude control.
  - ii) Constant output power devices; fast phase modulation can move power into sidebands, which will be reflected back from the cavities —> amplitude control with a single device.
- Potential for high efficiency at moderate price.
- R&D effort should be increased.

State of the art:

Type	Gain [db]	$P_{out, pulsed}$ [kW]	$P_{out, CW}$ [kW]	V_{input} [kV]	T_{pulse} [ms]	$T_{rise/fall}$ [ns]	efficiency DC to RF [%]	frequency [MHz]
CPI econo	25	?	100	20	any	?	70	826 - 929
CCR/CPI	25	100	10	22	10	ns	70	1300



65 kW, 500 MHz solid state amplifier at PSI (Marcos Gaspar, PSI)

Solid state

The Hype?

Solid state: examples

Type	$P_{\text{out, pulsed}}$ [kW]	$P_{\text{out, CW}}$ [kW]	V_{input} [kV]	T_{pulse} [ms]	$T_{\text{rise/fall}}$ [ns]	efficiency$_{\text{DC to RF}}$ [%]	frequency [MHz]	comments
ELBE	16 kW	16 kW	-	0.001 - 100	0.02/0.06	47%	1300	
R&K	16 kW	16 kW	-	any	0.01/0.01	36%	1300	forced air/water
Tomcod	-	10 kW	-	-		45%	700	up to 80 kW
R&K	-	20 kW	-	-		?	509	forced air/water
PSI	~70 kW	~70 kW	-	any	0.045	~50%	500	grid to RF
Cryoelectra	-	45 kW	-	-		51%	500	
LNLS	-	25 kW	-	-		57%	472	
ESRF	70 kW	70 kW	-	any		55%	352	DC-RF
Soleil	30 kW	30 kW	-	any		50%	352	DC-RF, 180 kW
Tomco	-	10 kW	-	-		55%	350	up to 110 kW
Cryoelectra	-	16 kW	-	-		46%	118	
Siemens	-	18 kW	-	-		75%	72.5	
Cryoelectra	-	115 kW	-	-		57%	72.8	
R&K	60 kW	60 kW	-	any		56%	1.8	
State of the art	10 - 100 kW	10-100 kW	-	any	10-60 ns	45-55%	0-1300	
potential?								
R&D:	48 kW	-	-	3000		60%	352	up to 400 kW
Thales	135 kW	135 kW		-			200	test at CERN

Solid state: examples

Type	$P_{\text{out, pulsed}}$ [kW]	$P_{\text{out, CW}}$ [kW]	V_{input} [kV]	T_{pulse} [ms]	$T_{\text{rise/fall}}$ [ns]	efficiency$_{\text{DC to RF}}$ [%]	frequency [MHz]	comments
ELBE	16 kW	16 kW	-	0.001 - 100	0.02/0.06	47%	1300	
R&K	16 kW	16 kW	-	any	0.01/0.01	36%	1300	forced air/water
Tomcod	-	10 kW	-	-		45%	700	up to 80 kW
R&K	-	20 kW	-	-		?	509	forced air/water
PSI	~70 kW	~70 kW	-	any	0.045	~50%	500	grid to RF
Cryoelectra	-	45 kW	-	-		51%	500	
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ESRF	70 kW	70 kW	-	any		55%	352	DC-RF
Soleil	30 kW	30 kW	-	any		50%	352	DC-RF, 180 kW
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Thales	135 kW	135 kW		-			200	test at CERN

Solid state pros/cons

1) Modularity.
2) Hot swapping of faulty systems.
3) Short rise time.
4) No limitation in pulse lengths or rep rate.
5) No high-voltage.
6) No loss in efficiency below WP
7) Prices are falling.

1) Combination of 100s of single units is complicated and can be lossy.
2) Depending on architecture, reflected power may be an issue.
3) Limited DC to RF efficiency 45 - 55%.

Solid state

State of the art, developments

State of the art:

- Frequency range 0 - 2.5 GHz. Lower efficiency and power output/transistor for frequencies > 700 MHz.
- Single units in the order of 1 kW.
- At present maximum power < 200 kW.

Developments:

- Use of **combiner cavities** instead of combiners.
- Industry does **not need higher power transistors** but they may need **higher efficiency transistors,** which would become a **game changer.**

CERN needs & developments

present machines: Linac3, SPS, LHC
future projects: FCC, CLIC, HL-LHC

High-power RF at CERN

> 100 kW

Machine	Type	P [MW]	f [MHz]	T_{pulse} [μs]	Rep rate [Hz]	$N_{Systems}$	N_{units}
Linac2	Tetrode	0.1 - 2.7	202	350 - 1000	1	11	18
Linac3	Tetrode	0.3 - 0.7	101/202	350 - 1000	1 - 10	4	8
Linac4	Klystron	1.2 - 2.8	352	1000	1	14	14
REX	Tetrode	0.1	101/202	1000	1 - 100	6	6
RFQD	Tetrode	1.7	202	150	1	1	2
PS	Tetrode	0.1	2.6 - 9.5	< 200 ms	0.8	2	6
PS	Tetrode	0.4	40/80	300	0.8	5	15
SPS	Tetrode	1	202	10 µs - 5 s	43 kHz/0.1 Hz	4	88
SPS (LIU)	SSA	1 - 1.4	202	10 µs - 5 s	43 kHz/0.1 Hz	2	32
SPS	IOT	0.24	808	10 µs - 5 s	43 kHz/0.1 Hz	2	16
LHC	Klystron	0.3	400	CW	CW	16	16
XBOX 1,2	Klystron	50	12000	1.5	50	2	2
XBOX 3	Klysstron	6	12000	5	400	1	4
Total						**70**	**227**

High-power RF at CERN

> 100 kW

Decommissioning
2019

Machine	Type	P [MW]	f [MHz]	T_{pulse} [μs]	Rep rate [Hz]	$N_{Systems}$	N_{units}
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Established/renewed
in the last 5 years

High-power RF at CERN

Decommissioning
2019

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RFQD	Tetrode	1.7	202	150	1	1	2
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Ongoing development

High-power RF at CERN

Decommissioning
2019

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REX	Tetrode	0.1	101/202	1000	1 - 100	5 +1	5+1
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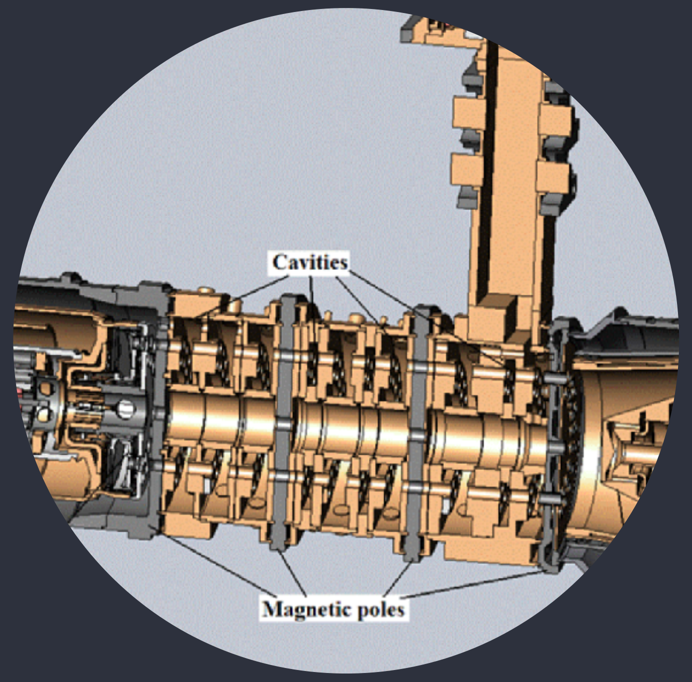
Established/renewed
in the last 5 years

Ongoing development

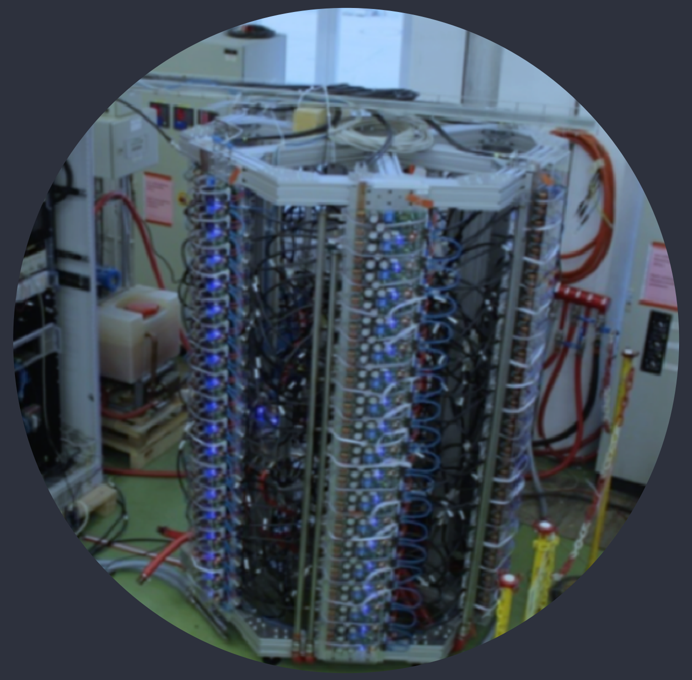
Planned exchange with
SSA

CERN R&D on HP RF sources



Klystrons: Igor Syratchev et al., i) high-efficiency klystron development within HEIKA: 3 GHz PoP done, CSM method developed, active development of klystron simulation code KlyC, 704/800 MHz (ESS/FCC) development started, first ideas for 400 MHz (LHC/FCC). ii) high-power (50 MW) X-band test stand for high-gradient X-band structure testing.

MB-IOT: Eric Montesinos et al., high-power test stand established at CERN. 2 ESS MB-IOTs have been tested. Further tests possible (but not foreseen). Unlikely that MB-IOTs can compete with high-efficiency klystrons.

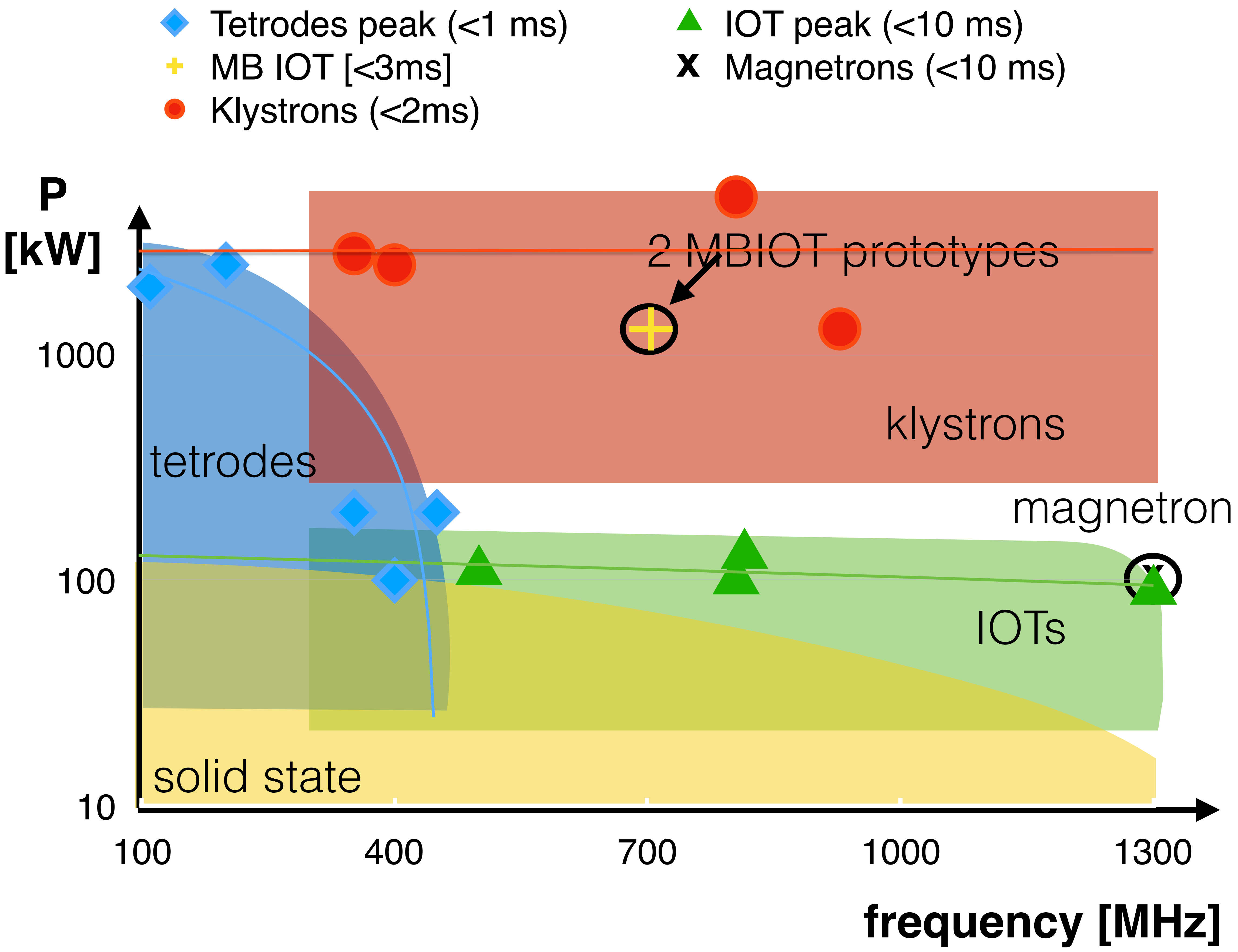


Solid State: Eric Montesinos et al., development of combiner cavity and application for LHC Injector Upgrade (LIU): addition of 2 x 1.4 MW, 200 MHz to the SPS RF system, based on 32 SSA towers (if successful). Green light expected in Sep. 18. Probably the highest power SSA system in the world.
Planned replacement of 2 Linac3 100 MHz tetrode amplifiers (300 - 400 kW).

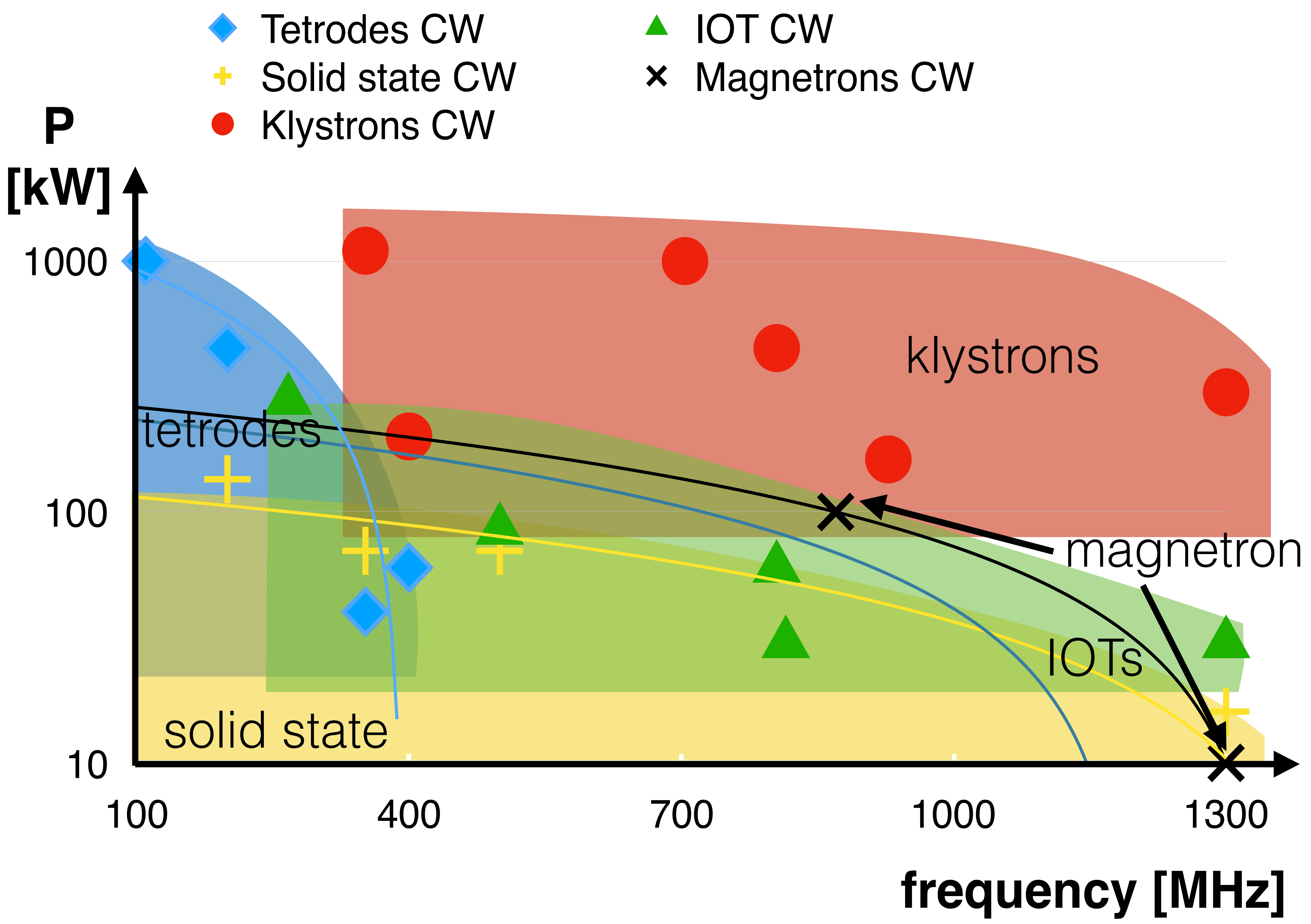
Summing up

Power/frequency chart

Pulsed Operation



CW Operation



Parameter overview

parameter	Tetrodes	IOTs	klystrons	solid state	magnetrons
gain [db]	15	20	40-45	stacked	25
output power pulsed [kW]	4000	130/1300	1000 - 15000	0 - 150	100
output power CW [kW]	1500	100/150	1200	0 - 150	100
HV needs [kV]	10-25	< 50	90-120 (60*)	-	20
pulse length [us]	any	any	~4 ms	any	?
rise/fall time [us]	ns	ns	0.3	0.01 - 0.06	?
DC to RF efficiency[1] [%]	**~70**	**~70**	**~55 (>70*)**	**~45 - 55**	**~70***
frequency [MHz]	30 - 400	? - 1300	300 - 1500	0 - 1300	400 - 1300
active development	no (Diacrode)	2 MB-IOT	yes	yes	little

*under development, 1 - at working point

My personal view

- **High-efficiency klystrons** are mandatory for our future machines. Lower price, higher efficiency, shorter, lower voltage, higher power, ….
- Klystrons are today the only RF sources for MW-class power > 300 MHz.
- **MB-IOTs** have similar efficiency but can probably not compete on price.
- **Solid state** is rapidly developing towards higher power but the efficiency remains modest. Nevertheless they start competing with tetrode systems < 300 MHz. Industry does not need higher power transistors but they may need **higher efficiency transistors**, which **would be a game changer**. Important to efficiently combine single units, e.g. with **combining cavities**.
- **Tetrodes** seem to decline, even though very efficient and reliable, but probably not enough customers.
- **Magnetrons:** High potential for lower prices and higher efficiency. More effort needed.

THANKS

FOR

Listening